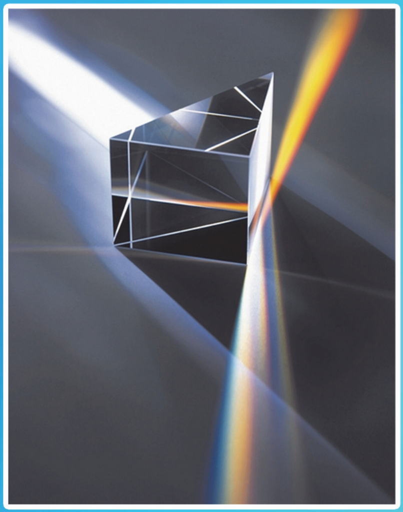
Quality Assurance of Precision Optics



OP-TEC

National Center for Optics and Photonics Education

Precision Optics Series

Quality Assurance of Precision Optics

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

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FORWARD

Precision optics is a critical U.S. industry from both an economic and security perspective, and precision optics technicians (POTs) are vital to the quality and future growth of this industry. These technicians produce, test, and handle optical components that are used in lasers and sophisticated electro-optical systems for defense, homeland security, aerospace, biomedical equipment, remote sensing, alternate energy production, and nanotechnology. Precision optics technicians also measure quality, add coatings and integrate optical components into electro-optical systems.

In 2009, the National Center for Optics and Photonics Education (OP-TEC) conducted a study of POT employers to project the demand for new precision optics technicians. The findings of this study showed that 6019 POT technicians were currently (2009) employed, and that the demand in five years would increase by 3100 additional precision optics technicians.

In 2012, OP-TEC updated and produced the second edition of the National Precision Optics Skill Standards for Technicians. The Standard provides the precision optics community and educators an updated listing of what technicians working in the precision optics industry should know and be able to do. It was developed from an extensive and comprehensive review process involving precision optics industry professionals and academic representatives, and has received endorsements from the American Precision Optics Manufacturers Association (APOMA), Colorado Photonics Industry Association, New Mexico Optics Industry Association, and the Rochester and Florida Photonics Clusters. This Standard has formed the basis for the design of OP-TEC's AAS degree POT curriculum. It also provides the "industry specifications" for developing these instructional materials.

Two of the courses in the curriculum are *Quality Assurance of Precision Optics (QAPO)* and *Interferometry and Metrology*. These courses can be infused into OP-TEC's Photonics Technician curriculum to prepare technicians to measure the quality of precision optics and integrate them into laser and other electro-optics systems. The full AAS degree POT curriculum is built on a manufacturing technology core, and prepares technicians who can not only perform the tasks described earlier, but also fabricate precision optics components.

OP-TEC, the National Center for Optics and Photonics Education, is a consortium of colleges and industry groups working to increase the supply of well-educated optics and photonics technicians by building and strengthening the capacity and quality of optics and photonics education in U.S. two-year colleges. By empowering community and technical colleges to meet the urgent need for new technicians and retraining workers in optics and photonics, OP-TEC plays a significant role in maintaining our country's economic competitiveness and military preparedness, and ensuring that highly rewarding jobs will be available for American citizens, including its veterans. OP-TEC is funded by the National Science Foundation to provide information about optics and photonics technology and technician careers, curricula and teaching materials, faculty professional development, and technical assistance to colleges and high schools. Twenty-nine colleges form the OP-TEC Photonics College Network.

Daniel Hull, PI
OP-TEC   2013

PREFACE

The three instructional modules contained in this course are designed for use by students and instructors involved in the preparation of technicians in the area of precision optics fabrication and photonics. Educators can use this course as an introduction for an AAS program in precision optics fabrication and as an elective in an AAS laser-electro-optics program. Corporate trainers can use it in programs designed to retrain or update the skills of engineering technicians who are already employed. This course can also support dual-credit offerings for high school students in STEM career pathways.

The National Center for Optics and Photonics Education, OP-TEC, developed this course under NSF ATE Grant number 1144377. Content specifications were determined from the 2nd Edition of The National Precision Optics Skill Standards for Technicians, available at www.op-tec.org.

Acknowledgements

The original manuscript of this course was authored by Brian Monacelli, Senior Research Scientist at the Optical Sciences Company (tOSC) and Photonics Instructor at Irvine Valley College and was edited by John Souders (OP-TEC). OP-TEC greatly appreciates the technical input provided by Nicolaus Lambert and Adrian Hoyle from Precision Optical. Their reviews and input have added substantially to the quality of this course. OP-TEC also wants to thank Al Lambert, Al Lambert Jr., Ben Felter, Steve Huebel, Fred Schwind, Javier Arreola, Rodney Guzman, Kim Tran, Paul Dimeck, and Marty Runningwolf, also from Precision Optical, and Erik Fleming, Pete Lagunas, and Randy Elmore of Diverse Optics Inc. Fabrication shop and laboratory images were graciously provided by Precision Optical, Schott North America, Inc., and the University of Central Florida Center for Research and Education in Optics and Lasers (CREOL).

GLOSSARY

The material presented in this course involves technical terms and measurement techniques that are often unique to the field of precision optics. To make certain users have the vocabulary needed to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of this course. Terms in the glossary will be italicized throughout the course material.

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Fabrication of Precision Optics

Module 1

of

Quality Assurance of Precision Optics

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

PREFACE TO MODULE 1

This is the first module in the *Quality Assurance of Precision Optics (QAPO)* course. This course provides an overview of processes used to manufacture precision optics elements; introduces quality assurance (QA) practices required to identify, inspect, and measure optical components; and presents a comprehensive review of measurement practices essential to ensuring the quality of optical components. This course is designed for students seeking a basic understanding of how precision optics components are produced and what techniques are used to validate their adherence to industry standards. This course was designed to comply with the 2nd Edition of the National Precision Optics Skill Standards for Technicians.

Module 1, Fabrication of Precision Optics, addresses precision optics manufacturing processes. It covers the fabrication of transmissive and reflective optical materials, the assembly of optical components, the procedures for applying optical coatings, and the techniques used to form lenses, mirrors, and diffractive optical elements.

The material presented in this course involves technical terms and measurement techniques that are often unique to the field of precision optics. To make certain users have the vocabulary needed to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of this course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary will be italicized throughout the course material.

CONTENTS OF MODULE 1

Module 1
Fabrication of Precision Optics

INTRODUCTION

Any substance that interacts with light can be called an optical material. Common objects such as windows, beverage glasses, lighting reflectors, and even chandelier crystals are all made with optical materials. These objects allow light to pass through or bounce off their surfaces, but the quality of the image formed through these materials is not always important, so often, the material's optical qualities are not important. By contrast, devices such as eyeglasses, video displays, and cameras all contain precision optical materials. The quality of the images formed through these devices is very important. No one is surprised if a scene looks blurry through a beverage glass, but if a scene looks blurry through your camera, there is something wrong either with the alignment of the lenses (for instance the focus) or with the composition of the glass. Precision optics are integral to high-quality imaging and illumination.

This module presents an overview of the precision-optics fabrication process, from the selection of materials to the coating of the finished optical element. It may seem odd that a module on fabrication is introducing a course on quality assurance. We do this because fabrication and quality assurance are very tightly tied together. Quality assurance is the verification that the processes used to fabricate optics were conducted accurately and to the standards required by the customer. Because fabrication is so important for quality assurance, we begin this course by describing the fabrication process for precision optics. In subsequent modules, we will show how the fabrication process uses quality assurance to ensure that the optics produced in fabrication meet the strict tolerance codes and high quality standards of today's precision optics industry.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers:* Modules 1-1, 1-2, 1-4, and 1-5

Students should be able to calculate ratios, perform dimensional analyses of units, understand the use of geometric equations to describe conic sections (parabolas, ellipses, etc.), and use trigonometric formulas
(which requires successful completion of high school algebra, geometry, and some trigonometry).

OBJECTIVES

- Recognize the differences between precision optics and other materials that interact with light
- Describe each step of the fabrication process required to make a precision glass lens, from melting raw material to deposition of an antireflection coating on a polished substrate
- Describe each step of the fabrication process required to make a precision mirror on a metal substrate, from machining raw metal stock to deposition of a high-reflection coating with a protective overcoat
- Describe the processing steps required to make other optical-grade parts, including plastic and ceramic parts
- Describe the difference between amorphous, polycrystalline, and monocrystalline optical materials
- Identify materials that may be used for transmissive and reflective optics
- Describe various thin-film deposition technologies required to apply an optical coating on a precision optical substrate
- Identify the various flaws that may be present within the bulk of transmissive optical materials, including glasses and plastics; these potential flaws include
    - grain boundaries
    - bubbles
    - discoloration
    - inhomogeneities
    - striae
    - internal stress
    - inclusions
    - impurities
- Identify the various flaws that may be present in optical coatings, including the following
    - stress
    - porosity
    - scratches
    - digs
    - impurities
- Define the radius of curvature and focal length of a spherical optical surface

- Describe aspherical and freeform optical surfaces and how they are used to improve the imagery of an optical system
- Describe how an optical surface can be structured to diffract light
- Describe the properties of optical materials that are deliberately made to absorb light

SCENARIO

Alexa has always been interested in the materials from which things are made. In high school, she discovered that she was interested in chemistry because it helped her understand the structure and composition of various materials. This understanding motivated her to continue her education in precision optics and use her education to test and evaluate optical elements such as lenses, mirrors, prisms, and windows.

After graduating from a precision optics program at a community college, Alexa was hired as a material inspection technician in an electronics company that makes touch-screen displays for cell phones and hand-held video game consoles. Alexa works with an engineering team to ensure that the materials the company receives from raw materials vendors meet their high corporate standards. In a day’s work, she is required to assess the properties of a number of pure, optical-grade materials. In a typical work week, she might measure and compare the refractive index of coated Schott B270® and Schott D263® sheet glasses on Monday and Tuesday, study their spectral transmissivity on Wednesday, and prepare a report of her measured results on Thursday in preparation for a discussion with the engineering team on Friday morning. Her diverse, hands-on experiences testing the sheet glasses make her a valuable part of the production team—she helps her company stay at the cutting edge of the display market.

BASIC CONCEPTS

What Makes an Optical Material a Precision Optical Material?

To turn raw materials into precision optics, many different processes have to be followed carefully. Careful evaluation of the part is required at each step, and even the processing materials must be examined in detail to assure quality fabrication. Precision optics may be constructed from a variety of materials, including glasses, crystals, metals, ceramics, and plastics. The fabrication methods depend on the material itself and on whether the optical element will be transmissive or reflective. In all cases, materials change form, from natural raw substances, to ordinary materials, to machined optical parts, to precision optical components. This transformation is achieved by enhancing the purity of the optic's composition and shape at each step of the fabrication process. A thorough understanding of fabrication processes will help technicians working on fabrication and metrology teams as they troubleshoot to determine which aspects of the processes could be improved to produce superior parts.

Fabrication of Transmissive Optical Materials

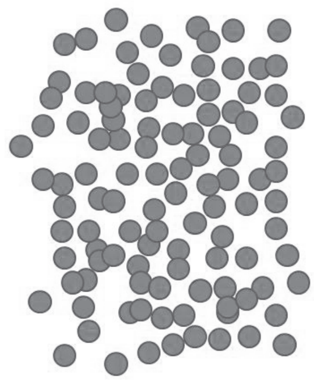


Glass Optical Substrates

For the best example of the transition from raw material to a precision optical element, consider the formation of a basic transmissive optical material from a readily available raw material: sand. The most common sand is silicon dioxide (SiO_2), and though many other chemicals are present in natural sand, SiO_2 is particularly important because it may be used to describe the two most common types of transmissive optical materials: *amorphous glasses and crystals*.

Please keep in mind that to ease communication in the field, most transparent optical materials are typically referred to as "glass," regardless of their structure. You even may hear some optical plastics loosely referred to as "optical glasses" because, for many applications, they do a similar job.

Glass fabrication processes are well established—people have been fabricating glass for thousands of years. The transition from sand to glass occurs by a thermal process known as *rapid melt quenching*. In this process, sand is heated to a liquid form (at around 2000°C) so that all its molecules may flow around freely within a container. As in any liquid, as molecules move, they randomly reposition themselves. Then, the liquid is rapidly cooled (quenched) so that all the molecules are essentially frozen in place. Since there is no particular organization to the molecules, the resulting solid material is known as *amorphous* (without form). Amorphous, pure silicon dioxide defines a glass known as *fused silica*. In fact, most optical glasses are composed of silicon dioxide along with other chemicals that are mixed into the liquid before quenching. These chemicals are added to alter the optical properties of the glass.

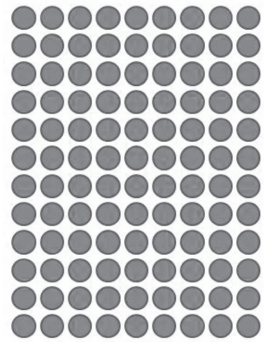


Atomic structure of an amorphous material

The most common additives to silica glass for windows and other typical applications are soda ash and lime, or, to use their proper respective chemical names, sodium oxide (Na_2O) and calcium oxide (CaO). Glass made from these materials is called *soda-lime glass*. For optical applications, other kinds of silicate (i.e., silicon dioxide–based) glasses are more typical. *Crown glasses* have low refractive indexes due to the addition of potassium oxide (K_2O), boric oxide (B_2O_3), or other molecules, while *flint glasses* have high refractive indices due to the incorporation of potash lead in the form of lead oxide (PbO), titanium dioxide (TiO_2), and zirconium dioxide (ZrO_2). For environmental and health reasons, titanium oxide and zirconium dioxide have become more common than lead oxide.

This section primarily covers silicate glass. However, the processes that are discussed for silicate glass also apply to other materials that have applications in the infrared and ultraviolet region of the electromagnetic spectrum. For instance, calcium fluoride (CaF_2) and magnesium fluoride (MgF_2) are often used to form precision optic components for use with ultraviolet light. For infrared light, zinc sulfide (ZnS), zinc selenide ($ZnSe$), and other materials classified as chalcogenides are used.

When a liquid raw material (e.g., the sand) is quenched, it cools very rapidly. But if a liquid melt is cooled more slowly, the molecules or atoms of the melted raw material can line up, or *crystallize*.



Atomic structure of a crystalline material

Crystallization takes place naturally, given the proper pressures and temperatures during the transition from liquid to solid. Most natural crystals have optical properties that are appealing to the eye, but they cannot be used for precision optics, because their structure is somewhere between amorphous and crystalline form. They are organized in tiny crystalline clumps or grains with boundaries between each clump or grain. The grain boundaries in these polycrystalline materials scatter light. This is the reason that it is usually difficult to see through an ice cube. Ice cubes are typically cooled at a rate that generates a polycrystalline internal structure. Because they scatter light, polycrystalline materials are not very useful as transmissive optical materials.

The phenomenon of molecules or atoms fully crystallizing, or “lining up” within a material, is essential to the optical properties of transmissive materials. A fully crystalline material is known as a *monocrystalline* material. Polycrystalline materials, or materials that are only partially crystalline throughout their volume, are not as desirable for optics. This concept is quite intuitive, considering this analogy: When standing at the edge of a natural forest, the partially organized locations and orientations of the foliage on trees and bushes make it difficult to see light transmitted from the other side of the forest. However, when foliage is deliberately ordered, as in an apple orchard or grape vineyard, it becomes possible to see light transmitted from the far side. Notice the difference the next time you ride past a natural forest and a man-made orchard. The orchard is ordered and represents, so to speak, a crystallized structure in two dimensions. From now on, this course will use "crystalline" to refer only to monocrystalline materials, since those are used to make optics.

Crystalline materials also have different optical properties, depending on the structure and orientation of the molecules or atoms that compose them. In particular, the refractive index of the resulting optical material may depend on the direction that light travels through the crystal with respect to the orientation of its structure. This useful phenomenon is known as *birefringence*.

In review, transmissive optical materials may be *amorphous* or *crystalline*. The choice of material depends on the desired properties of the precision optical element.

Flaws within Transmissive Optics

From a quality-control perspective, producing high-performance optics begins with controlling the transition of the raw material into amorphous or crystalline solid forms. It is critical to understand the thermal history of the optical component to be measured, or else it will be difficult to locate the root cause of its flaws and improve fabrication processes.

Amorphous and crystalline materials are subject to similar flaws during their fabrication. An obvious flaw is the creation of polycrystalline regions within either an amorphous or crystalline material. Polycrystals are defined by the presence of grain boundaries that scatter light. Such boundaries are caused by inadvertent crystallization within amorphous optical materials and by insufficient or improperly oriented crystallization within monocrystalline optical materials. The scattering sites presented by these *grain boundaries* are not acceptable in precision optical materials.

Other materials are often deliberately added to the mixture during the melt to alter optical properties. Materials that are added for specific purposes are called *dopants*, but undesirable materials that happen to enter the melt are called *impurities*. They create flaws that range from bubbles formed by trapped air within the structure to unexpected chemicals that cause localized absorption, scattering, or even an overall discoloration. Discoloration results from a uniform absorption of particular wavelengths throughout the entire material.

The rate of temperature change and the material distribution within an amorphous glass during thermal processing will affect the final material's internal uniformity. Changes to this uniformity may cause *striae*, or lines of refractive index inhomogeneity within the bulk material.

If different parts of the optical material are cooled at different rates, internal stresses can form. These stresses may affect both the optical and the mechanical properties of the glass. They change the path that light takes as it transmits through the material, and they can also cause structural damage as the glass changes temperature, possibly resulting in a crack or chip. *Internal fractures* may also form due to localized stress within the materials. In the case of crystalline optics, grain boundaries or impurities can cause *inclusions*—defects to the crystal matrix that forms the optic. A high number of inclusions can render an otherwise fully monocrystalline material useless for optical applications. For example, so-called “milky quartz” is monocrystalline but contains so many inclusions that light cannot be transmitted through it.

Any of the many defects listed here can occur during thermal processing. Before the materials even begin to look like a lens or other optical component, the processing of precision optics has to be carefully controlled. Look closely at old or inexpensive glass: bubbles, striae, and internal fractures will be evident. Even airplane windows contain tiny internal fractures and bubbles. Whether or not you're flying first class, your window is probably not a precision optic!

In review, the thermal processing of all glasses must be carefully controlled to prevent a variety of flaws, including grain boundaries, bubbles, internal stress, inclusions, and impurities. Maximum tolerable values for most of these flaws will be specified in the drawing of the optical element supplied by the optical designer.

Processing the External Surfaces of Transmissive Optics

As the melt cools, glass is cast (shaped) into bulk blocks, strips, molds, and sheets of glass for production into optical elements. Once the glass is fully cooled, solid, and stable, the material's internal structure as a precision optic is fixed and complete. Now, the material's exterior may be carefully shaped into optical elements by cutting, shaping, grinding, and polishing it. In short, the glass will be smoothed into the desired shape. These techniques remove the extra material, bumps, divots, and subsurface damage to form the material's surface into a final shape, which will depend on its application. This section details the processes required to fabricate optics from raw bulk glass.

Cutting processes gradually reduce the size of the optics until they are only slightly larger than the final optics, a form called *near-net shape or raw machined blank*. The first cutting step involves cutting the large glass blocks into manageable pieces from which many optics can be made. Cuts need to be made in an efficient manner that will not waste the bulk material, so cuts are made with a sharp, hard, diamond-blade saw, like the one shown in Figure 1-1.

Figure 1-1 *Large band saw for initial cutting of raw material*

The next cuts form pieces of glass that encompass the shape of each optical element. These cuts are made using tools such as the circular saw shown in Figure 1-2. Cutting processes require particular care when working with crystalline materials, because the orientation of the crystal structure is aligned with an axis of the final optical element. The surface of the crystalline optic is aligned to be parallel to the rows and columns of the crystal. This careful type of cut may enhance the optic's mechanical stability when it is mounted.

Figure 1-2 *Circular saw for intermediate precision cutting*

Next, shaping processes cut the bulk part to a piece that resembles the final optic, but without the precision surface shape and finish. An optic in this form has machined, ground edges; it is translucent and scatters light, and it is still far from the clear finish of a precision optic. When bringing many parts to near-net shape, it is wise to process many optics at the same time. This may be accomplished by using wax to mount the parts to be cut onto a flat plate, as shown in

Figure 1-3, so that the parts may be simultaneously cut using a tool such as the rotary grinder shown in Figure 1-4.

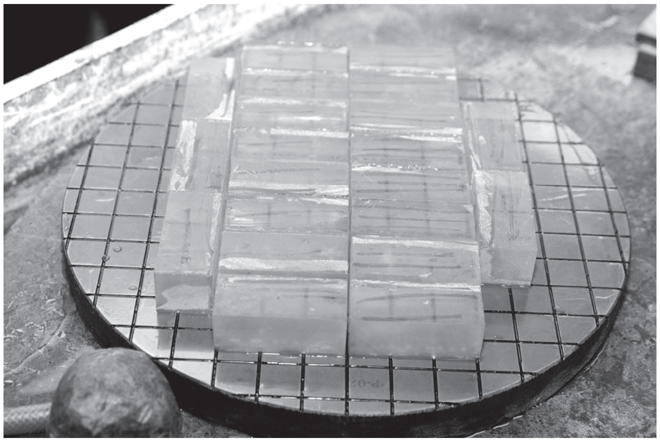


Figure 1-3 *Wax block on parallel metal plate*

Figure 1-4 *Setup of a parallel machining operation*

Other machinery used to bring the part to near-net shape include lathes and multiple-axis computerized numerical control (CNC) milling machines. Each optic must be fabricated with the proper edges, cores, bevels, chamfers, and custom facets that form the non-optical surfaces of the part. These features facilitate handling, mounting, and other application-specific requirements. Feature sizes are typically specified to a few tens of micrometers during shaping.

Precision shaping of optical and non-optical surfaces is accomplished using frequent in-process measurements and custom tooling. For instance, if an optic needs to have two perpendicular surfaces, the right angle can be achieved by referencing and matching the optic to metal master tooling that has been determined beforehand to nearly match the shape of the final optical element. The optic may be moved many times between a measurement station, such as a height gauge on a granite slab, and a cutting system to ensure that the proper shape and size is achieved.

As an example of features on non-optical surfaces, consider the edging of a mirror substrate. Safe, proper edges are required for all optics. Most optical systems require circular-aperture parts, but machining processes cut rectangular pieces. To make the input faces circular, the corners of the pieces must be cut around their periphery. This process is known as *edging*. It is accomplished using a lathe-like cutting machine such as the one shown in Figure 1-5.

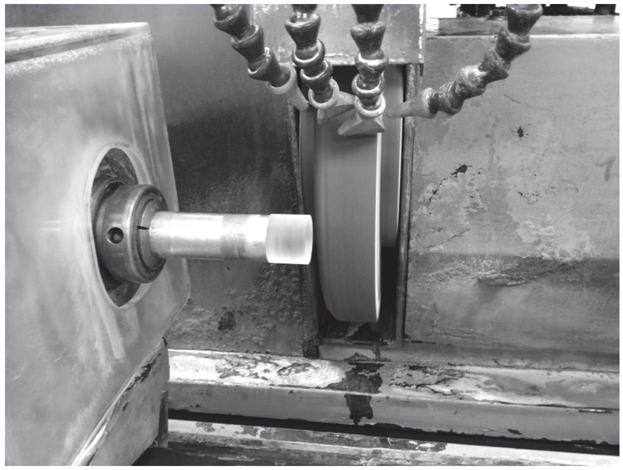


Figure 1-5 *Mirror substrate being edged to diameter using diamond wheel and edging machine*

Edging takes parts such as the one shown on the left side of Figure 1-6 and changes them into circular parts, such as the one shown on the right side of Figure 1-6.

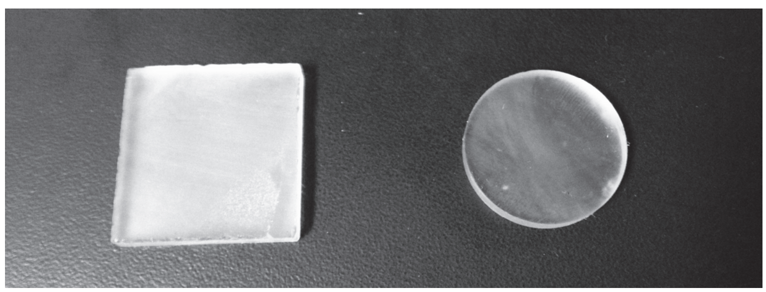


Figure 1-6 *Mirror substrate before and after edging*

The material is now sized only slightly larger than the final part and is at near-net shape. Next, the glass goes through a course grinding process that employs large, hard, abrasive particles, or grits, to remove major surface irregularities and sub-surface damage before it is polished to its final form. During grinding, abrasives are located between the optical material being processed and cast iron. During polishing, abrasives are located between the optical material being processed and a viscoelastic (dense, springy) material called *pitch* or *a polyurethane pad*. The pitch is bonded to a metal or granite mounting structure, and the pitch is then shaped to form the optic into the desired shape. When forming curved spherical lenses, the pitch has a shape that is the inverse shape of the desired optical surface. For example, if a concave surface with a spherical radius of –50 mm is desired, the pitch surface will be convex with a spherical radius of +50 mm, a perfect mate to the final optical surface. Of course, manufacturing a flat optical surface requires a flat pitch.

Following grinding, the final mechanical process is polishing. This involves moving even finer abrasives over the surface of the glass in a careful, repeated manner to form the surface into the exact shape that the optical designer prescribed. This is why the process of polishing is often called *finishing*.

Grinding and polishing may be accomplished by hand in conjunction with machinery or by using computer-controlled machines. The mechanical processes of grinding and polishing may be familiar by analogy to the simple process of washing with a bar of soap. The soap starts out as a jagged, pitted material. After a number of uses, it is ground down to a smooth, uniform shape—one that can make it slippery to hold! Some examples of tools used in grinding and polishing are shown in Figure 1-7.

Figure 1-7 *Upper left: Hand grinding a block of prisms*

Upper right: Precision hand grinding an individual prism

Bottom: Continuous polishing machine that is pitch-polishing various substrates

The optic is ground or polished as the worker's hands or automated motors vary the pressure between the optic and the pitch and as the technician varies the speed of the moving pitch. The abrasive *slurry*, a mixture of abrasives and water, is placed between the optic and pitch, and gradually cuts the optic down to a smooth finish. Hand-finishing techniques involve moving the part above a spinning platform of pitch that is covered with an abrasive slurry. Often, master opticians polish optics to their final form using hand-finishing methods after having used automated systems to bring the optics closer to their final shape, as shown in Figure 1-8.

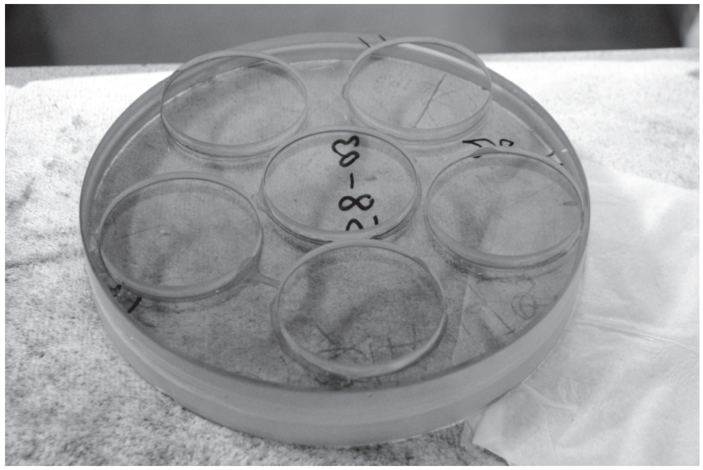


Figure 1-8 *Precision polished optical surfaces*

Mounting and Protecting Optics during Fabrication

During the grinding and polishing processes, a number of materials may be used to hold the parts and to mask surfaces that require protection. Holding materials can range from metal frames or plaster molds to adhesives such as epoxy or even beeswax, as shown in Figure 1-3. Masking materials may be paints, tapes, or metal sleeves. These are all temporary materials, so it is essential to consider appropriate removal techniques before the introducing a new material to the fabrication process. For instance, plaster may need to be hammered away, waxes are typically melted or scraped off, and most bonds and paints must be chemically stripped. The optical element may need to endure hammering, rubbing, heating, or chemical solvents to strip the materials that are holding or masking it during processing.

The following sequence of images shows a good example of a technique used to mount and mask precision optics (prisms, in this case) during their fabrication. Here, only one optical surface is being worked, but that surface will be simultaneously worked for many optics. Only the surfaces to be processed will be exposed. The entire assembly of parts must be accurately held in place during processing, and the other surfaces not being processed must be protected during the processing. As a first step, the precision optics technician uses a black paint to coat the surfaces not being processed, as shown in Figure 1-9.

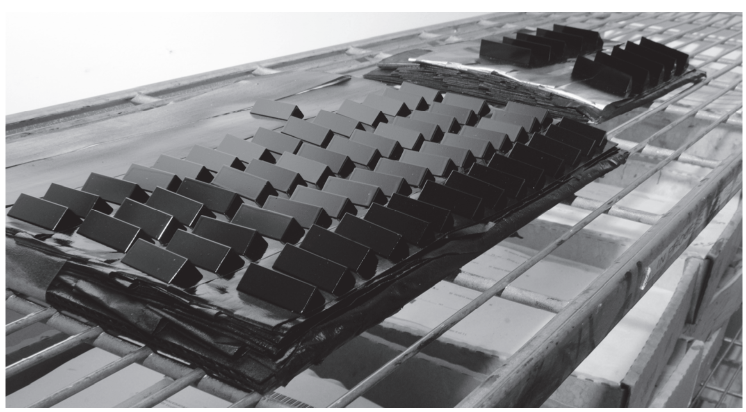


Figure 1-9 *Prisms painted to protect finished optical surfaces*

Then, the technician accurately orients and mounts an array of parts into an adhesive pitch compound, as shown in Figure 1-10, before they are surrounded in a plaster casing. With the plaster or pitch casing in place, the blocked parts are ready for polishing, as seen in Figure 1-11.

Figure 1-10 *Optics blocked in pitch*

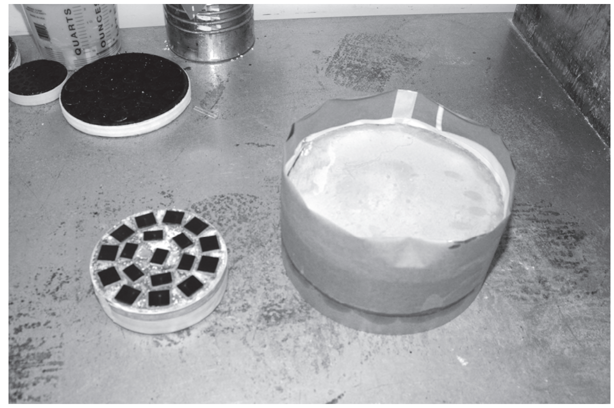


Figure 1-11 *Optics blocked in plaster*

After the optical surfaces have been processed, the plaster holding them in place must be carefully removed, as shown in Figure 1-12. It is certainly a fine skill to carefully remove plaster from around glass optics using a wooden mallet!

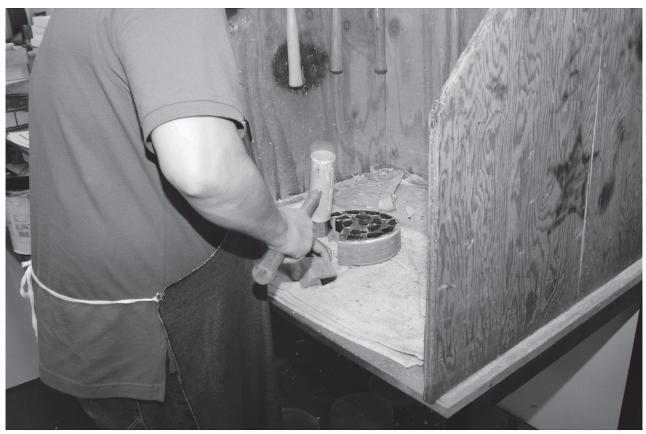


Figure 1-12 *Deblocking a plaster block*

After the plaster has been removed, remaining paint, plaster, and any other contaminants have to be stripped from the optics. This is done in a controlled, enclosed machine like the one shown in Figure 1-13. This system uses chemicals that remove the surface contaminants without affecting the underlying glass. The resulting stripped optics are shown in Figure 1-14. Complex steps such as these may be required for each optical surface during the grinding and polishing processes.

Figure 1-13 *Basket of paint-protected optics being loaded into a degreasing machine to remove pitch and plaster*

Figure 1-14 *Tooling optics in degreasing basket*

The Finer Cuts: Grinding and Polishing Process Parameters

The abrasive particles that are used for shaping, grinding, and polishing are usually specific to the material being polished, but they are always made from an extremely hard material such as cerium dioxide, zirconium dioxide, diamond (crystalline carbon), or sapphire (aluminum oxide). Cerium oxide is the most common; though it is not as hard as other abrasives, it is much less expensive. Abrasive particles are fine—typically 0.01 to 3.0 µm in diameter. The abrasive material must be harder than the optical material itself, or the process will work poorly, or even in reverse, with the optic rubbing the grits down to dust!

Particles of these hard materials are mixed with water or another lubricating fluid to make a wet, muddy compound that is known as a *slurry*. This slurry is then rubbed by hand, by a motorized arm, or by a complex computer-controlled system over the optical material at specific pressures and rates, using finer abrasives as the process advances from the ground material to a finished optic. Material removal information is well documented and, in general, follows Preston's formula, shown in the equation below. Preston's formula states that the amount of material removed during polishing, z, is proportional to the pressure applied, p; the speed between the glass and the polishing tool, v; and the time spent polishing, t. Preston's coefficient, C_p, has units of area per force and is related to the coefficient of friction between the glass and polishing compound.

$$z = C_p \cdot p \cdot v \cdot t$$

According to this formula, fast, high-friction polishing applied at high pressure for long durations will remove material fastest. However, fast material removal is not the goal of fine polishing, so this formula is used as a guide for selecting the right parameters for specific polishing applications. For instance, sometimes it is easier to make a polishing tool move faster, but it is not practical to apply more pressure. The key is to have a controllable, deterministic, and efficient polishing process.

Industrial experience has demonstrated that many other parameters of the polishing process can influence material removal rates. Preston's formula is just a starting point. Everything from the temperature and the pH of the slurry to the bond strength of the abrasive on the pitch has an effect on material removal rates and final surface roughness.

Example 1

Typical values for Preston's coefficient range around 10^{-7} square millimeters per Newton (mm^2/N) or 10^{-13} square millimeters per Pascal. Polishing may be performed over an area of A = 10 mm by 10 mm (100 mm^2) for a 50 mm optic, with a load of L = 50 Newtons at a velocity of v = 50 mm per second (for a typical turntable that rotates at about 10 rpm). Since pressure equals load per area, p = 0.5 Newtons per square millimeter (N/mm^2). The product of these values shows that only z = 9 μm of material is removed per hour of polishing!

Once finished, the polished optical material is referred to as a *substrate*, a term that defines the base material on which a coating is deposited. A coating is a thin layer of various materials that enhances the optical properties of the entire element. Coatings are the topic of the next section, but it is important to recognize that nearly all precision optical components will be coated.

The polishing processes described here have worked well for hundreds of years to polish flat and spherical surfaces. Spherical surfaces are straightforward to make and understand. Polishing a randomly rotating glass substrate will naturally result in a spherical shape. However, modern optical designs incorporate *aspherical*, *freeform*, and other complex surfaces, such as aerodynamic or conformal surfaces. Asphere shapes are described later in this module. Freeform surfaces are described well by their name—they are surfaces of any form that can be freely described, usually by a complex mathematical equation.

Hand-polishing techniques can be used to finish these advanced surface shapes if adequate and frequent measurements are made, but this iterative process is tedious and time consuming. To efficiently make aspheres, state-of-the-art fabrication processes are required. A revolutionary polishing technology called magnetorheological finishing (MRF) has greatly eased the fabrication of complex surfaces. In this commercial technique, the material of the optic is removed by a stream (a "ribbon") or jet of magnetic slurry containing carbonyl iron. Magnetic fields interact with the iron in the slurry during the polishing process. This interaction is carefully controlled to ensure that the slurry shapes the material into the optical element desired. This is a deterministic method of material removal, and it has been used to create many types of optical shapes from simple spheres to aerodynamic domes.

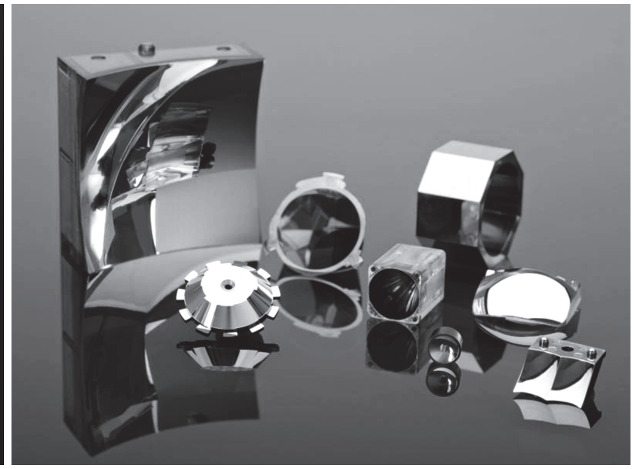
The fabricated optics are only as good as the ability to measure them. The advanced techniques and tools of optical metrology will be covered in a later module, but it is critical to recognize that measurements are integral to the grinding and polishing processes. A material will move between a processing step and a measurement step many times before it is finished. Some of the most helpful metrology techniques may be performed *in situ* (that is, without moving the part), but most require the optical surface to be cleaned of the slurry and dried. When properly polished, each cycle between polishing and measurement brings the material to a form that more precisely resembles the final desired shape: the surface becomes less irregular, and the image seen through it becomes clearer.

Glass is the most commonly used optical material. The examples here illustrate how glasses are manufactured; most are processed in a similar manner. However, there are many types of glass and crystalline optical materials available, and each has slightly different optical properties, depending on its structural form (i.e., crystalline versus amorphous) and its chemical constituents. Table 1 lists some of the types of glass available from the manufacturer Schott.

Table 1 *A variety of common glass types for visible and near-infrared light*

Different Types of Glass	
Glass Type	Schott Symbol
fluorite crown	FK
phosphate crown	PK
dense phosphate crown	PSK
borosilicate crown	BK
barium crown	BaK
dense crown	SK
crown	K
lanthanum crown	LaK
very dense crown	SSK
barium light flint	BaLF
crown/flint	KF
lanthanum dense flint	LaSF
lanthanum flint	LaF
barium flint	BaF
barium dense flint	BaSF
very light flint	LLF
light flint	LF
flint	F
dense flint	SF
zinc crown	ZK
special short flint	KzSF

Plastic Optical Substrates



Plastics are another increasingly common transmissive optical material. Plastics undergo fabrication processes that are similar to those of glass, but less intensive. Plastics, or polymer optics, are traditionally used in applications that require much less precision and lower tolerances. Plastic optics can be found in magnifiers, inexpensive cameras, illumination lighting, medical devices, wearable optics, laser beam formatting, and optoelectronic components, such as light-emitting diodes (LEDs) and photo receivers. Manufacturing processes have significantly improved since plastic optics became mainstream in the mid-1990s, so plastics are becoming more a desirable option for the optical designer because they are less expensive to make quickly. Their lower purchasing costs primarily derive from lower fabrication costs and fewer fabrication steps, as compared with glass. Plastic optics may be more desirable than glass because of plastic’s lower mass and the ability to integrate plastic optics directly into mounting hardware. This hardware isn't just attached or glued to the plastic optic, but instead may be made a part of the same plastic material, in the same process step in which the optic itself is fabricated.

Polymers begin as compounds derived from virgin resources (seldom are recycled materials optical grade). Optical plastics are usually thermoplastic resins; a few of the most common are listed with their optical properties in Table 2. They are available in rod, bar, sheet, or pellet form. Let's further examine the fabrication of plastic optics via either injection molding or single-point diamond turning (SPDT).

Table 2 *Properties of Optical Plastics*

Technical Name	polymethylmethacrylate (PMMA)	polycarbonate (PC)	polystyrene (PS)	cyclic olefin copolymer (COC)	cyclic olefin polymer (COP)	polyetherimide (PEI)	crown glass	flint glass
Trade Name	Acrylic, Lucite, Plexiglass, Polycast	Lexan, Merlon	Styron, Lustrex	Topas	Zeonex, Zeonor	Ultem	N-BK7	N-F2
Refractive Index								
n_F (486.1nm)	1.498	1.599	1.604	1.54	1.537	1.689	1.522	1.632
n_d (587.6nm)	1.492	1.585	1.59	1.534	-	-	1.517	1.62
n_D (589.3nm)	1.492	1.585	1.59	1.534	1.53	1.682	1.517	1.62
n_C (656.3nm)	1.489	1.58	1.585	1.531	1.527	1.653	1.514	1.615
Abbe value	55 to 57	30	31	56	56	19	64.17	36.43
Rate of Refractive Index Change with Temperature (dn/dT)								
[10^{-5}/°C]	-8.5	-11.8 to -14.3	-12	-10.1	-8	N/A	+0.16	+0.2
Visible Light Transmission								
[%]	92	85 to 91	87 to 92	92	92	36 to 82	91.6	88.4
Coefficient of Thermal Expansion (CTE)								
[10^{-5}/°C]	6.74	6.6 to 7.0	6.0 to 8.0	6.0 to 7.0	6.0 to 7.0	4.7 to 5.6	0.710	0.784
Maximum Continuous Service Temperature								
[°C]	60 to 70	124	82	130	130	170	357	367
Hardness	Rockwell M97	Rockwell M70	Rockwell M90	Rockwell M89	Rockwell M89	Rockwell M109	Knoop 610	Knoop 420
Impact Strength								
[ft-lbs/ in notch]	0.30 to 0.50	12.0 to 17.0	0.35	0.50	0.50	0.60	N/A	N/A

Table 2 presents standards and nomenclature common in the precision optics industry. For example, the subscript on the index of refraction, n_d, refers to the d-line of helium (587.56 nm), and the other subscripted quantities in Table 2 under the heading "Refractive Index" refer to other spectral lines. The unit of the CTE, $10^{-5}/^{0}C$, provides a measure by percentage of how the dimensions of an object change when its temperature changes a certain number of degrees

Celsius. The term *notch* in the unit for impact strength refers to a physical notch made on an object to induce failure in a specific location during hardness testing. These standards and nomenclature are the means by which precision optics professionals communicate with one another and must be mastered to effectively work in this industry. Other modules in this precision optics series will cover these standards more rigorously and will provide more in-depth explanations of commonly used terms.

Fabricating Plastic Optics

Injection molding involves using a master mold to make many optics by replication. All three types of raw polymer—rod, bar, and sheet—may be melted to a liquid and injection molded into a metal or glass mold. Figure 1-15 shows an example of an injection mold.

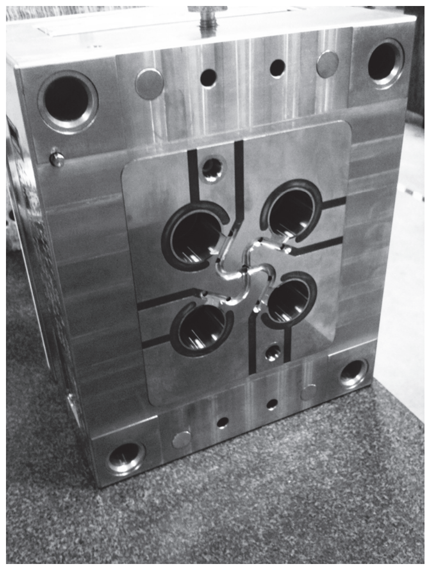


Figure 1-15 *Optical plastic injection mold*

Since the molds form the baseline shape, they need to be of higher precision than the final plastic optics. A mold for an optic of any shape only needs to be fabricated once, and replication of many optics is then straightforward. Inconsistencies between the master mold and the replicated optic may be due to impurities in the polymer material, interactions with the mold, and problems with the cooling rate (as is the case for glass optics). Molds are typically made from thermally stabilized steel that has been nickel plated. The nickel layer will form the shape of the polymer optic, and this layer is diamond-turned to the form of the final optic. Though post-polishing techniques for plastic are being developed, plastics are seldom post-polished currently, because plastics are too soft and polishing techniques deteriorate the surface finish.

A second technique for forming plastic-based optical elements is called *single-point diamond turning* (SPDT). SPDT uses a hard, sharp, diamond tool embedded in a special computer numerically controlled (CNC) machine to cut the part to its final shape. This machine is a combination of a lathe and a mill—typically, CNC machines work by moving the part in a rotating chuck in three axes about a stationary diamond tip or by moving the diamond tip in three axes about the rotating part. An example is shown in Figure 1-16. A multiple-axis CNC machine can easily cut complex shapes such as aspheres and domes, although the optical precision of the final plastic parts is not very high. After machining, some plastic optical materials may benefit from a thermal anneal to release stresses induced by the machining process.

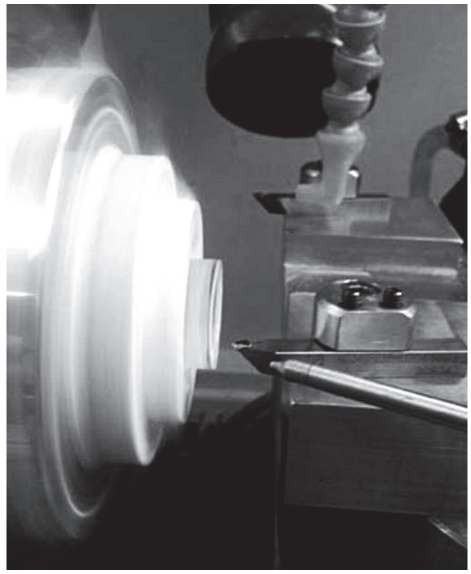


Figure 1-16 *Single-point diamond turning (SPDT) system cutting a plastic lens*

Fabrication of Reflective Optical Materials

Metals may be the first material you consider in making a reflective optical system, because metals naturally reflect light over a wide range of wavelengths. However, it is just as common to coat glass or plastic optical materials to make them reflective. In fact, coatings need to be applied even to naturally reflective metal optics to protect the metal mirror's finish and create the ideal reflectivity spectrum for the intended application. That said, most reflective optical materials are discernible from transmissive optical materials only because they are coated with reflective materials.

Glass and plastic can both serve as substrates for reflective optics, but there are two other important types of optical substrate materials, *metals* and *ceramics*, that are usually used only to make reflective optics. The following discussion highlights their fabrication.

Metal Optical Substrates

Metals make important optical components, but not because metals reflect light. Metals are primarily used for structural and thermal reasons. All materials change shape and size as temperatures change. This property of a material is called its *coefficient of thermal expansion* (CTE). In an optical system, the surrounding mechanical system that holds the optics is often made of metal. It is desirable for all materials in the optical system to be identical so that when the temperature changes, they all change shape at the exact same rates. This design technique is called *athermalization*. A metal optical substrate is a good choice if you need to create an athermal system. Metals also have the beneficial properties of high *stiffness* and *ductility*—that is, metals will not easily deform or fracture under stress.

Like glasses, metals undergo thermal processes to stabilize them for further processing and to help them reliably perform the function for which they were designed. Optical metals might be made of aluminum, beryllium, copper, brass, titanium, molybdenum, steel, or composite metal materials. Aluminum is by far the most common, and beryllium is used for applications that require lightweight metals.

Raw optical-grade metal blocks, sourced from metal ore (again, seldom from recycled materials), are processed into optics using machine shop tools. They are cut to a near final shape using lathes or CNC milling machines. As an example, the most common metal mirror material is 6061-T6 aluminum alloy. Before this material is machined, it must be thermally stabilized via a thermal cycling process known as a T6 process. This involves dissolving all the alloying elements within the aluminum by raising its temperature to 980°F for an hour. Then, it is quenched (rapidly cooled) in water, so that the alloying elements do not precipitate. Finally, the material is brought to a T6 temper by elevating its temperature to approximately 350°F, thereby causing the alloying elements to form arrays within the aluminum matrix that considerably strengthen the bulk metal. The metal is then cut with a sharp, hardened-steel or diamond-point blade to form the optic. Cutting can form internal stresses that can be released by thermal processing, so thermal cycles are interspersed with the cuts to further stabilize the metal. After a thermally stable, near-net shape is achieved, the metal mirror will undergo a polishing process.

However, many metals are difficult to reliably polish. Aluminum has been called "buttery" during polishing—when the abrasive slurry is applied, the metal isn't polished as much as it is pushed around at the surface of the optic. Therefore, the stabilized metal base material, known as the *substrate*, is coated with an overcoat of another, harder metal that can endure the abrasive polishing process. Electroless nickel is the most common plating material, and it is this metal surface that is polished to the final finish.

Like plastic optics, metal mirrors have the advantage that they may be fabricated into complex shapes that contain tooling, mounting, and other assembly features in addition to their optical surfaces. The high mass of most metals may be viewed as a significant disadvantage, but weight reduction techniques can decrease mass while retaining metal's most attractive qualities: rigidity and durability.

Ceramic Optical Substrates

Ceramics can be made by a variety of processes, the most common of which are *sintering* and *chemical vapor deposition* (CVD). CVD involves the formation of a bulk ceramic structure by causing a chemical reaction between atoms or molecules to take place within a vacuum chamber, and then allowing the resulting ceramic compound to deposit down onto a substrate until a reasonable thickness of solid ceramic forms. For example, the ceramic silicon carbide (SiC) may be made using these techniques, either by sintering SiC powder into a bulk material, or by causing a chemical reaction between silicon and carbon. Additional materials may be included into the ceramic to enhance its structural properties.

Ceramics have the following advantages over metals: low density, high stiffness, low CTE, and the ability to be polished. However, they may be brittle, and they can be costly to manufacture. Like plastic and metal optics, ceramic mirrors have the advantage that they may be fabricated into complex shapes.

Table 3 compares the structural properties of some commonly used ceramics with those of metals.

Table 3 *Properties of Optical Ceramics*

Material/ Property	units	Invar	TA6V	Al 6061	ULE	Zero-dur	Si	SiSiC (30%)	C-SiC	Sintered SiC	SiC CVD	Be
Density, ρ	g/cm^3	8.1	4.4	2.7	2.2	2.5	2.3	2.9	2.6	3.1	3.2	1.8
Modulus, E	GPa	148	114	71	67	93	130	330	220	410	465	300
Thermal Expansion,TCE	ppm/DegK	1.3	8.6	23.9	.03	.05	2.6	2.6	2.0	2.2	2.2	11.5
Thermal Conductivity,Tc	W/mK	10.7	7.1	167	1.3	1.6	155	155	125	175	200	216

Optical Assembly

Sometimes, two or more optical elements must be precisely aligned into an optical assembly. A multielement optical assembly differs from an optomechanical assembly in that there are no mounting structures to keep the two or more optics together. The optics are either (1) bonded together with an optical, index-matching adhesive or (2) brought into optical contact—a process that takes two extremely clean and matched (either flat on flat or concave on convex) optical elements and causes them to bond together due to surface forces. The latter technique is much less common for commercial systems.

A common example of an optical assembly is the fabrication of a beam-splitter cube from two right-angle prisms. To begin this process, the precision optics technician cleans both surfaces to be mated. Then, one surface is faced upward. The technician applies the optical adhesive to this surface and places the second surface in contact as shown in Figure 1-17.

Figure 1-17 *A precision assembly technician applying optical adhesive to the hypotenuse surface of a right-angle prism before bonding it to another right-angle prism to create a beamsplitter cube*

The interface is pressed together and rubbed around until an adhesive layer completely fills the gap between the two surfaces. The interface is agitated to promote an even spreading of the adhesive and to remove air bubbles that may have been trapped during the assembly process. After the bond has been made, measurements of the assembly are taken. If measurements reveal that the assembly is close to its specification, thin shims can be inserted at the edges of the interface for final alignment. If measurements reveal that the assembly is too far out of specification to be shimmed, the parts can be separated and cleaned, and the assembly process can be restarted. After precision assembly and alignment is achieved, the bond is cured by ultraviolet irradiation; this process is often accelerated at elevated temperatures in a dry oven.

Optical Coatings

The final step in the fabrication of any precision optic is to apply thin layers of various materials, known as a *coating*, to the exterior of the substrate. The process of applying this coating is called deposition. Deposition is a complex and multivariable science, so an overview is provided here. Optical coatings may improve light's transmission through or reflection from a material in a way that is appropriate for its intended application. Coatings are spectrally selective; that is, they are designed to make the precision optic transmit, reflect, or absorb a particular region of the electromagnetic spectrum.

Coatings may serve other purposes, such as protection of underlying coating layers and the polished substrate from mechanical (e.g., scratches and impacts) or chemical damage (e.g., water or acids). In fact, hardened, hydrophobic coatings are common on expensive, high-performance sunglasses. Metal reflection coatings, such as aluminum, silver, or gold, are used when the natural properties of the metal can literally shine through. Only the metal layer itself is optically significant, but metal coatings require a base layer to promote adhesion, as well as a protective dielectric overcoat layer, somewhat like the clear coat of a car's paint finish. This protective layer must be durable without influencing the optical performance of the metal film. Coatings may even act as the electrical conductor or binder layer to help the substrate optical component interact with another part of the system. For example, all touch-sensitive screens (which are really flat optical windows) are created by including a conductive coating layer within the window.

Optical coatings can be seen on consumer optics. A common coating material that is intended to improve the transmission of visible light is magnesium fluoride. A thin layer of MgF_2 is applied to glass substrates to make them antiglare. Such a coating is known as an antireflective or AR coating. The thickness of the coated layers is paramount to their performance. The thickness of a MgF_2 glare-reducing layer measures one-quarter wave of visible light (555 nm), making them about 140 nm thick. These MgF_2 coatings may appear as a faint purple color and are often seen on eyeglasses and on the slanted windshields of vans and trucks.

Multiple layers of a dielectric material (i.e., an electrical insulator rather than a conductor) may be coated on a substrate to enhance reflection or transmission. Such coatings must be carefully deposited to ensure that each layer has the proper thickness and composition. This adds cost and complexity to their fabrication, depending on the required complexity of their spectral performance.

Optical Coating Deposition

Coatings are applied via many techniques, but three are typically used: evaporative, sputtering, and epitaxial growth. All three require an extremely clean environment. Precision coating techniques involve deliberately releasing the material to be deposited from its source to the substrate, on an atom-by-atom or molecule-by-molecule basis. As single atoms or molecules are freed from the source, it is necessary to increase the likelihood that they will actually land on the intended substrate before contaminant particles do. For this reason, the substrate, the coating source material (known as the target material), and the local environment must be carefully cleaned of any contaminants and impurities.

Substrates are cleaned by applying several fluids. Polishing slurries are typically water based, so they can often be removed from the surface of the optic with a rinse or submersion in a water bath. To remove additional contaminates, such as oil or grease, diluted alcohol or other solvents can be used. It is common to carefully clean a substrate with deionized water, methanol, or isopropyl alcohol before coating, but more resistant contaminants may require a stronger chemical, such as acetone or methyl ethyl ketone (MEK). Extreme care must be taken when selecting the appropriate cleaning chemical—it must not damage or react with the underlying substrate. Not only the substrate, but also the coating target materials must be clean, pure, and uniform throughout. They require surface cleaning in the same manner as the substrates to be coated.

Cleaning the environment is a challenge that has evolved into an entire discipline known as *vacuum processing*. The substrate and the coating source are located in the same metal or glass chamber, and the ambient air must be removed from the chamber's volume by evacuating or "pumping down" the chamber pressure to levels less than 1 millitorr. The target material is deposited on the substrate by one of many methods, the most common being evaporation, sputtering, and thin-film epitaxial growth. For all these techniques, lower vacuum levels (i.e., lower pressures) increase the probability that the target material will land on the substrate before a contaminant does. As contaminants are evacuated from the local, vacuum-chamber environment, the pressure drops, and the target material can more readily make the trip to the substrate. As a rule of thumb, a single layer (a "monolayer") of most coating materials deposits on a substrate every second at a microtorr (10^{-6} torr) of pressure

Deposition Techniques for Optical Coatings

When using *evaporative* coating methods, the coating target material is boiled thermally, as on a stove, or using a high-energy beam of charged particles such as electrons or ions. The resulting evaporated material rises to coat the substrate material that is located above the target material. This is like steam from a boiling pot of water coating your glasses when you remove the pot's lid. Appropriate rates of deposition must be calibrated for each set of materials and substrates. In fact, it is equally important to calibrate the appropriate rates of substrate cooling after application of the coating. If the coated substrate cools too quickly, the coating can delaminate (peel away) from the substrate. If that happens, you will have to start over again by thoroughly cleaning the substrate.

A substrate could also be coated when the material to be deposited (the target) is bombarded by a third material, called the *sputterant*. This method, known as *sputtering*, creates a fog of the coating material that accumulates as a film on the substrate surface. That is, the deposition of the target material on the substrate occurs through a process that is similar to how dew coats grass on a foggy morning. The sputtering particles are created by ionizing a gas to create a plasma.

It is common in the sputtering process to coat a substrate using a metal target while introducing a controlled amount of oxygen, nitrogen, fluorine, or a similar gas into the environment to create a chemical reaction that forms an oxide, nitride, or fluoride of the metal. It is critical to keep in mind that any materials present in a vacuum chamber could, in principle, react to become part of the coating, and therefore part of the optic itself. Proper quality control should recognize that an unintended compound may have found its way into the mix.

Epitaxial growth requires even lower vacuum levels than evaporation and sputtering and involves highly controlled processes. These extremely well-controlled processes are essentially crystal-growth processes in which each atom or molecule of the thin film coating is able to line up in the proper orientation within the crystalline matrix of the substrate.

Coating deposition is a delicate science, and many of the best coating vendors have their own tricks to improve coating adhesion, durability, and spectral performance. These tricks can be as simple as throwing a moist cloth into the coating chamber to alter the humidity during coating, or as complex as adding special gas concoctions into the chamber during a coating run to promote chemical reactions between the gas, the substrate, and the coating material. When testing an optical component, it is important to understand the entire coating process for that part, so that flaws may be traced to their cause.

Not all optical surface treatments are applied by adding a coating. Some surfaces are formed by patterning the optical substrate's exterior. When this is required, a sacrificial layer is usually applied using the deposition techniques described above or by spin-coating a liquid layer that can be later hardened by ultraviolet curing or thermal processing (baking). This sacrificial layer may be sensitive to light or electrons, so a specific pattern is then written into the surface by either photolithograpy or electron-beam lithography (EBL). (The term "lithography" literally means to write in stone. This is the technique by which computer circuit boards and other electronics are fabricated.) When these technologies are applied to an optical substrate, the features written are usually periodic patterns that are formed by deposition (adding material in only certain locations) or etching (removing specific material). These processes enable the fabrication of essential optical components, including diffractive gratings and computer-generate holograms (CGHs).

Coating Flaws

As with substrate material flaws, maximum tolerable values for coating flaws will be specified in the drawing of the optical element. Maximum values are also specified in standardized documents such as MIL specs (e.g., military specification MIL-PRF-13830B for scratches and digs, and MIL-C-48497A for abrasion and environmental conditions).

Possibly the most common flaw in coatings is the existence of *stress* within the coating. This effect, often present in the coatings of metal mirrors and thick dielectric stacks, is often compensated by coating and carefully cooling one side of the substrate, and then applying a stress-compensating coating layer on the reverse side. Alternatively, stress may be compensated during polishing by deliberately distorting the optical surface when it is polished. The concept of coating stress may be familiar if you have ever painted on ordinary paper. Hardened paint creates a coating on the paper that contains a great deal of tension relative to the paper itself, and this tension causes the paint to curl or even pull away from the paper.

Another common coating flaw is *porosity*. As a coating material deposits on a substrate, it naturally forms random islands of the material on the surface until a full layer of coating material forms, bringing all the islands together to form a monolayer. If the deposition rate is not well controlled, the islands will not be able to fully merge, which will create voids in the film. A porous coating is a detriment to the optical performance because void sites do not interact with light in the same way that the coated regions do. In addition, if the coating is an overcoat layer intended to protect the underlying structure, any porosity in this coating can leave parts of this structure exposed and vulnerable to damage. A porous coating will actually trap water on its surface, rather than cause it to bead up and run off. Porosity also leads to poor durability and resistance to environmental conditions.

Scratches and *digs* are superficial coating flaws that are relatively simple to understand, but they can greatly affect the optical performance of a coating. Scratches are lines that are cut along the outer surface of a precision optical element, and digs are tiny pits in the surface. Both can cause scattering sites that limit the transmission through and optical quality of a surface.

Coating Chamber Fixtures

Everything within the coating chamber can find its way into the optical coating. All coating processes are rife with opportunities for contamination. Therefore, it is crucial to properly orient the substrates to receive the coating material, to efficiently direct the coating material onto the substrate, and to keep contaminants out of the coating chamber.

Simple, removable metal baffles, as shown in Figure 1-18, should be included to keep the chamber clean between coating runs. These also can help regulate the temperatures inside the chamber, and they may be contoured to create the proper flow conditions for the coating materials to reach the substrate.

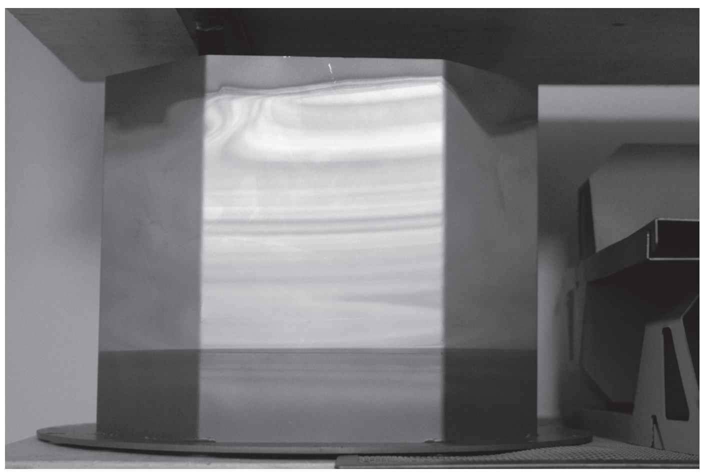


Figure 1-18 *Shielding for a coating chamber, contaminated after multiple coating runs*

For instance, it is not desirable for a coating material to hit a dirty sidewall of the chamber, thus releasing other unknown particles. Clean metal baffles that create a path from the target to the substrate will prevent such undesirable effects. Baffles need to be removed and cleaned as coating materials accumulate.

Optical Components: Lenses and Mirrors

Nearly all types of optics are fabricated using the techniques described in the previous sections. Their application dictates their function, shape, and quality. The most common optical components are lenses and mirrors, so this discussion will start with these basic components to show what features make these optical components *precision* optical components.

Lenses are pieces of glass through which light is transmitted. The path that light takes through the lens is dictated by the curvature of the glass surfaces and the glass material itself. It is critical to realize that light interacts with every surface and material it encounters. It refracts, reflects, or scatters at the first surface it hits; is refracted, scattered, or partially absorbed by any internal interfaces as it travels through the glass; and refracts, reflects, or scatters again at the exit surface. The shape and quality of the glass's external surfaces are extremely important factors in controlling these interactions with light, and the glass's internal structure must be essentially uniform and clean to maximize light's transmission and minimize its scattering. The phenomenon of refraction includes another, superficially subtle phenomenon called *dispersion*. When light propagates through glass, not only is it refracted, but different wavelengths of the light are refracted to different angles. This is effect is called dispersion.

Mirrors are most often formed from the same substrate materials as lenses, and then coated to be reflective. Therefore, these reflective elements require quality assurance assessments and measurements that resemble those for lenses. It is critical to note the type of reflection that takes place at mirror surfaces. Mirrors' shininess and smoothness make them excellent *specular* reflectors. This means that incident light reflects in a uniform, predictable manner from a mirror surface. Only well-polished reflective surfaces reflect light in a specular manner. However, when light encounters any surface, there will be some amount of *diffuse* reflection or *scattering*. In fact, lenses' non-optical surfaces (such as their peripheral edges and bevels) are deliberately ground so that they only reflect light diffusely. If they acted as specular reflectors, unexpected or *stray light* might transmit through the lens. Figure 1-19 shows the difference between specular and diffuse reflections. A mirror must be an excellent specular reflector to qualify as a precision optic. Typically, surrounding hardware is also ground so that it only diffusely reflects light.

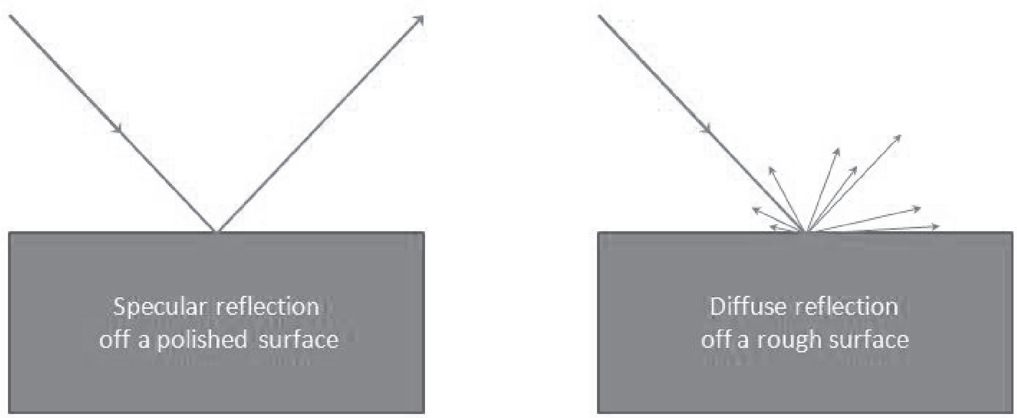


Figure 1-19 *Specular versus diffuse reflection*

Lenses and mirrors may have a variety of compositions, shapes, and sizes. They are usually organized and marketed based on two properties: their spectral transmission or reflection range and their basic size and shape.

As mentioned in the fabrication section, materials have diverse transmission and reflection properties. Common glasses transmit in the visible region of the spectrum, wavelengths of light from 400 to 750 nm, and into the infrared, up to about 2000 nm. If impurities are removed during the fabrication process, pure fused silica and crystal quartz lenses can transmit down to 150 nm and up to more than 3500 nm. Reflective dielectric coatings can be designed to cover almost any spectral range, and they can be made to selectively absorb certain regions of the spectrum while reflecting others. Coatings made by stacking dielectric materials typically make a structured reflectivity profile, whereas metal coatings, such as aluminum, silver, and gold, reflect light uniformly from the visible into the infrared, up to millimeter-wave radiation.

Once the lens or mirror substrate material is selected, the optical fabrication process begins with the shaping of its surfaces. When a flat surface is formed, it is called a *plano* surface. A positive surface is known as *convex*, and a negative surface is called *concave*. Most optics are either radially symmetric spheres or cylindrical with one axis of curvature. The parameter describing an optic's spherical shape is its *radius* of curvature, as shown in Figure 1-20.

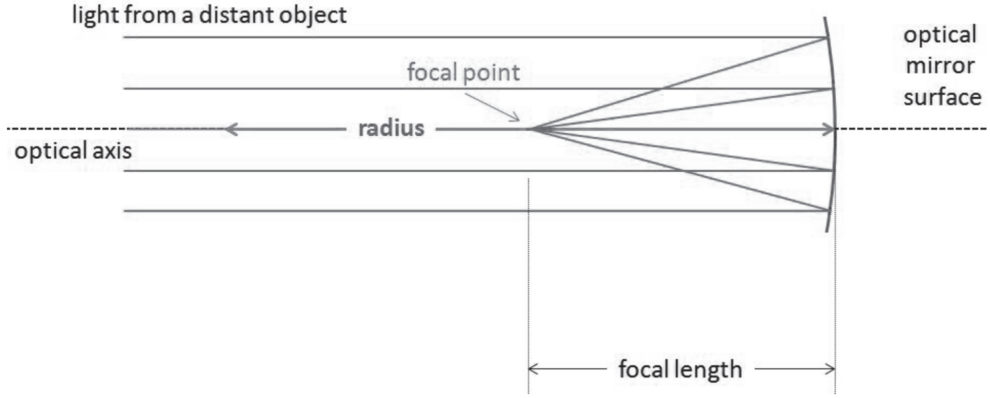


Figure 1-20 *Graphical definition of focal length and radius*

For spherical and cylindrical lenses, the *focal length* of a surface equals one-half of its radius. A cylindrical lens is really just a lengthwise slice of a cylinder—it has a cross section like a sphere in one plane, and a cross section like a flat in the perpendicular plane, as shown Figure 1-21.

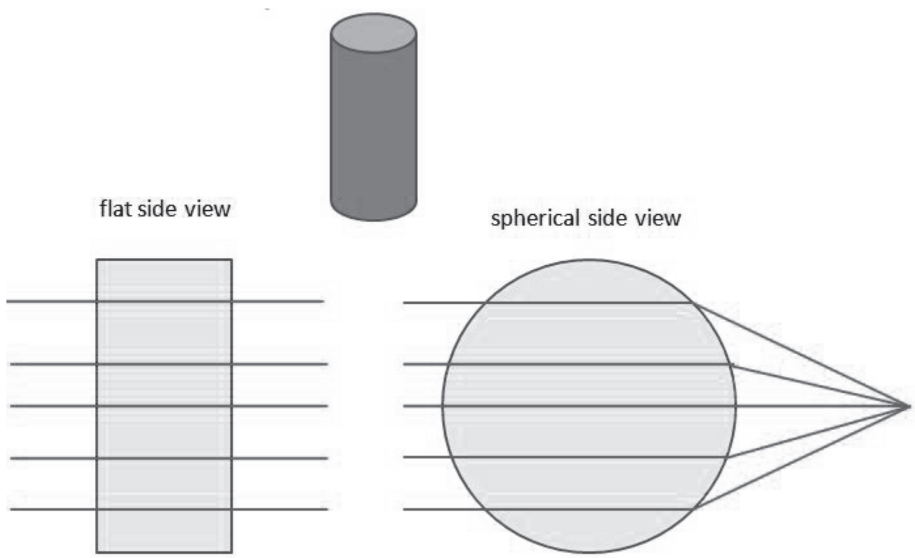


Figure 1-21 *Light propagating through cylindrical lenses*

Lenses always have two or more surfaces, and can be described using the following terms: *planoconvex*, *planoconcave*, *biconvex*, or *biconcave*. The term *meniscus* describes a lens that combines a convex and a concave surface into the same lens. If the lens's resulting focal length is positive because the convex surface has a higher curvature than the concave surface, it is known as a positive meniscus. In this case, it will be thicker in the middle than at the edges. Conversely, negative meniscus lenses are thinner in the middle than at the edges.

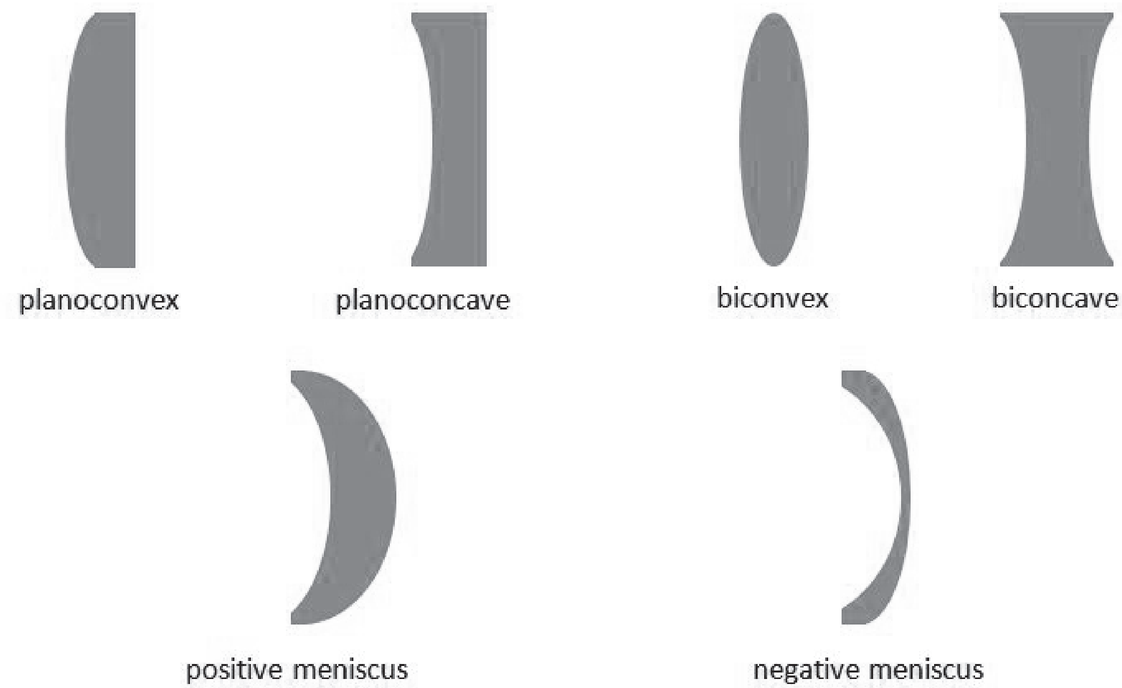


Figure 1-22 *Lens types*

Lens and mirror surface shapes may be more complex than spheres. A departure from a spherical surface is known as an *asphere*. Mathematically, an asphere is created by taking a conic section. This means that a cone is cut, as shown in Figure 1-23, and the resulting cross section is revolved around its axis to form a particular three-dimensional surface. From these 3D constructions, four different types of shapes can be formed, including a sphere, an ellipsoid, a paraboloid and a hyperboloid.

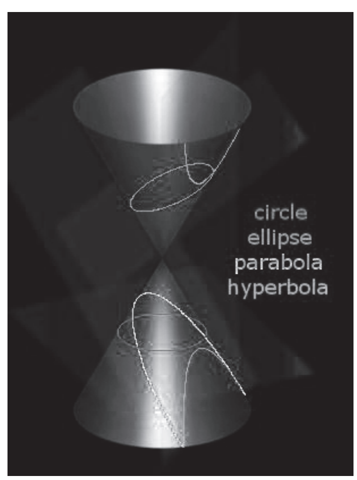


Figure 1-23 *Four different slices through a cone pair create the four types of conic sections that are used to make aspheric optical surfaces*

These are extremely important optical surfaces because these shapes create well-defined focal points for light. Images formed with these surfaces can be perfect and produce an exact point-to-point correspondence between an object and its image, under certain conditions. This exact point-to-point correspondence generates an *aberration-free* image. For instance, if light from a very distant object enters a paraboloidal mirror, a perfect image of the distant object will be formed at its focal point. This works in both directions. If a perfect image is required at a long distance, the object should be located at the paraboloidal mirror's focal point. Conversely, a spherical mirror produces a highly aberrated image of a distant object, particularly for the light rays incident far from the optical axis. As indicated in Figure 1-24, the paraboloid is a superior choice when perfect, aberration-free images of very distant objects are required.

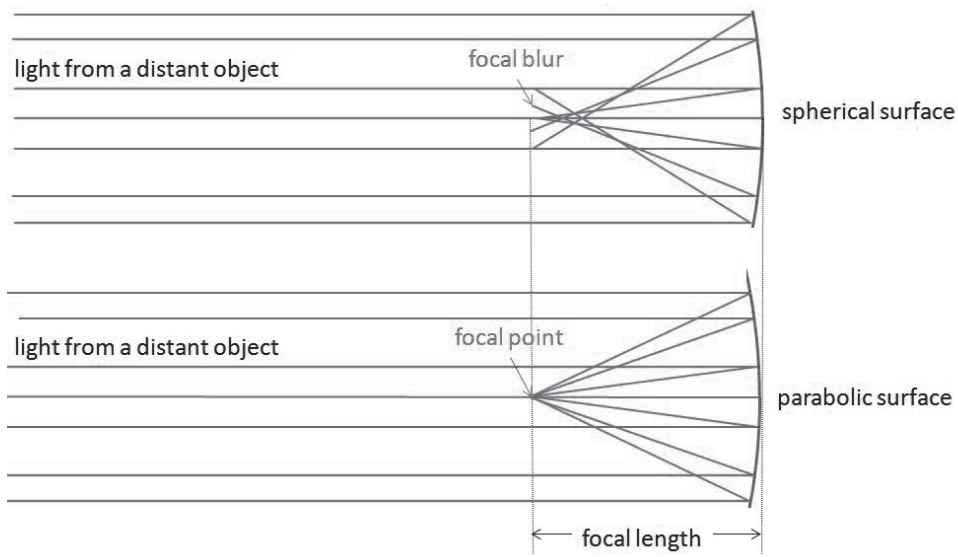


Figure 1-24 *Comparison of the images formed of a distant object by a spherical and paraboloidal mirror*

Ellipsoids and hyperboloids have two focal points. Light from one focal point will be perfectly imaged to the other focal point, and vice versa. This phenomenon can be sensed using sound waves in a whispering gallery, shown in Figure 1-25. This room is shaped exactly like an ellipse. If someone whispers at one of the ellipse's focal points, the sounds are clearly transmitted to the other focal point, so that a quiet whisper can be heard even if a large distance separates the two focal points.

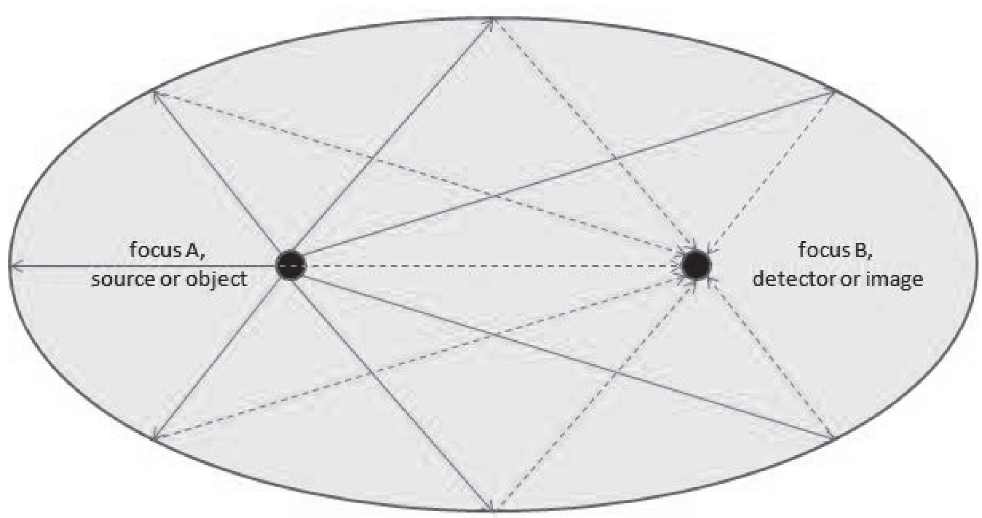


Figure 1-25 *Elliptical whispering gallery*

Optical surfaces may also have free-form shapes. These surfaces are described by complex topographical mathematical equations that are specific to the optical application. They have become common in illumination and communication optical systems. However, they can be extremely challenging to fabricate, requiring complex tooling and advanced polishing techniques, such as MRF or injection molding.

To fabricate and measure any optic (whether it is a sphere, asphere, or free form), it is necessary to know how far the optical surface deviates from a planar surface. This is called the *surface sag,* and it is illustrated graphically in Figure 1-26 for a sphere. The sag is given by the variable z(r) as a function of the radial distance from the optical axis.

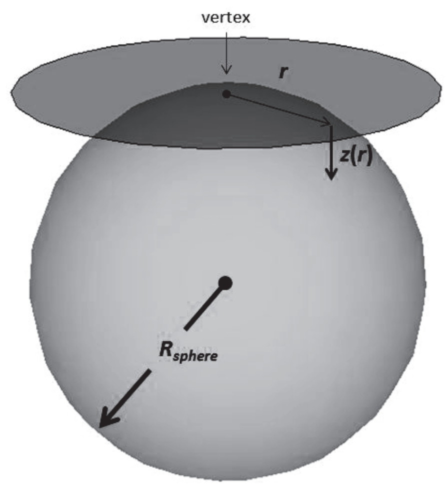


Figure 1-26 *Graphical definition of surface sag*

In Figure 1-26, the planar surface is represented by a circle that is tangent to the sphere at a point called the vertex. The vertex is the point where the optical axis of the sphere intersects the planar surface. The length of the line segment contained in the planar surface is the radial distance (r) from the optical axis. The distance, z(r), is the surface sag and defines how much the sphere deviates from the planar surface at radial distance r. For a sphere, the minimum value of surface sag is zero and occurs at the vertex (radial distance zero). The maximum value occurs at a radial distance equal to the radius of the sphere. The maximum value of z(r) for a sphere equals the magnitude of its radius.

Lenses with two flat optical surfaces are simply called *windows* or *wedges*. These can be used for actual windows, filters, beam splitters, beam deviators, polarizer substrates, and mirror substrates. In some applications, light may be intended to interact with more than two of the glass's surfaces, as is the case with the many types of prisms and solid retroreflectors that are used to reorient images. Typically, prisms contain flat surfaces that each interact with the light two or more times, as shown in Figure 1-27, which depicts light traversing through various types of prisms.

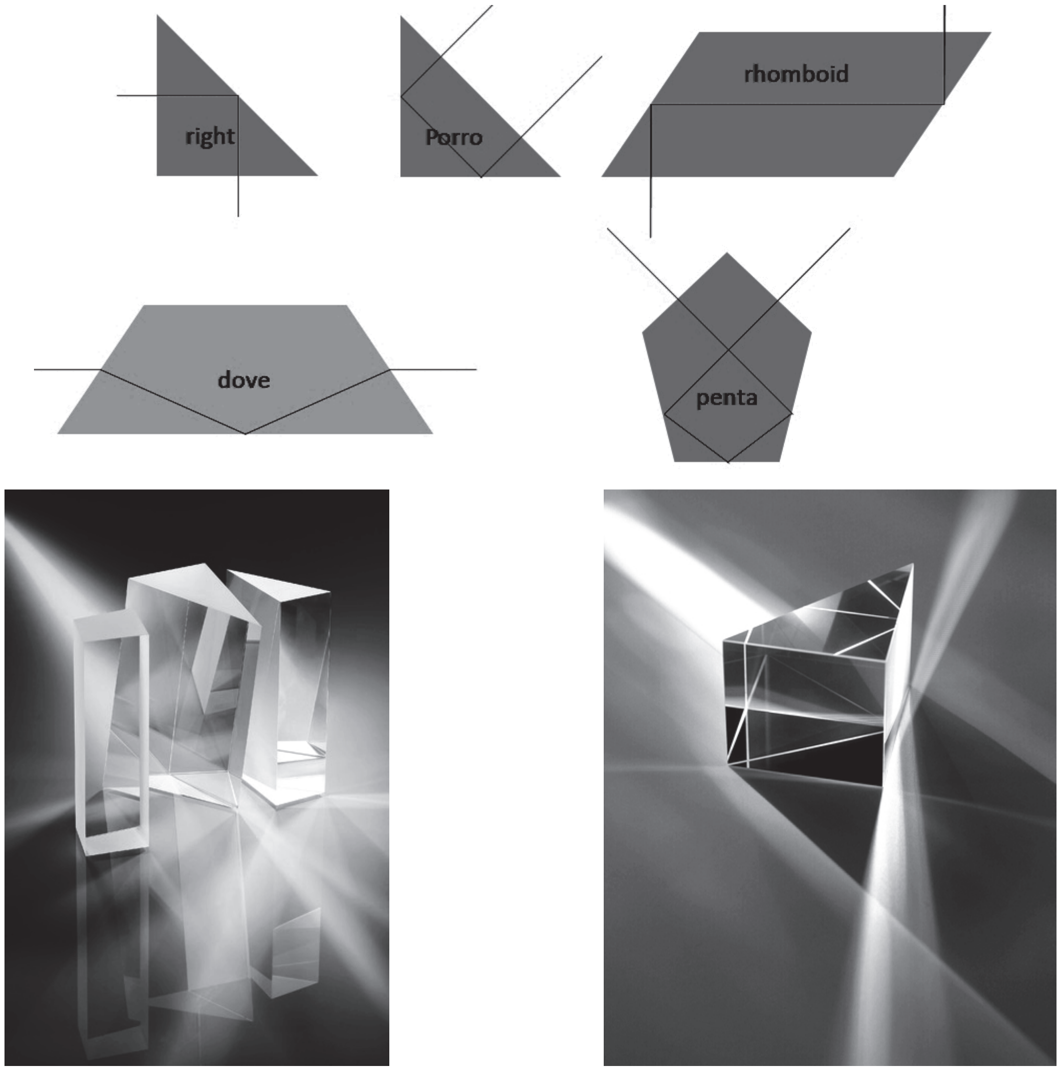
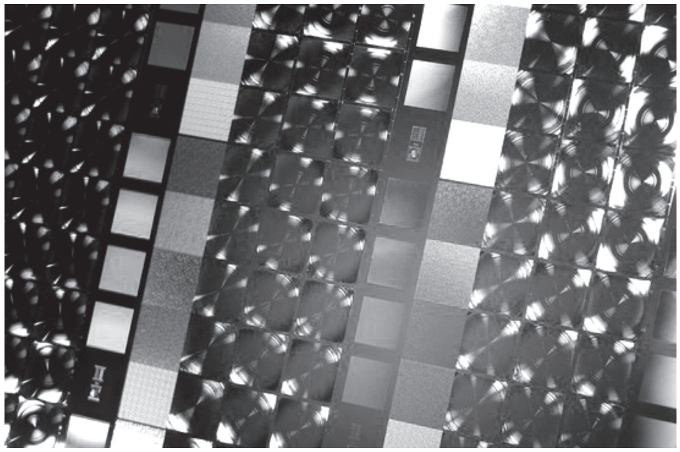


Figure 1-27 *Common types of prisms*

The many types of optical elements introduced so far can all be grouped together in terms of their quality control and evaluation, because the internal and external flaws that may be inherent in all of them are similar. For instance, most transmissive glass and crystalline elements are subject to comparable flaws, regardless of their shape. In fact, these elements size usually have the greatest influence on their evaluation options. In addition, the novel manufacturing processes that are required to make more complex shapes may add flaws with different characteristics.

Diffractive Optical Elements



Lenses and mirrors generally comprise the types of optical elements that are designed to transmit and reflect light. However, when light interacts with materials, a number of phenomena take place that are important to highlight now.

One interaction between light and materials is called *diffraction*. Diffraction occurs as light waves change direction and interfere with one another as they pass around the edges of tiny, periodically spaced apertures, bumps, or grooves in an optical surface known as a diffraction grating. This causes the light waves to overlap and interfere with one another. Constructive interference occurs for light traveling in many directions, and each direction is known as an order. The variable m represents the order of the diffraction. A prominent property of a grating is its *diffraction efficiency*, the ratio of the power of light diffracted into the desired order relative to the power of the incident light. The efficiency of a grating is controlled by the profile and shape of its grooves.

Diffraction gratings are usually fabricated via one of three methods: SPDT, holographic interferometry, or lithography. For the first technique, grating grooves may be mechanically scribed onto a metal substrate using a diamond tip that is moved in precise steps. This substrate may be used as the actual grating or as a master from which other gratings are replicated. The shape of the grating groove usually takes on the same triangular shape as the diamond-tipped tool, so it is an interesting challenge to control the diffraction efficiency of gratings fabricated by SPDT. The cutting tool must shape the grooves while maintaining a clean cut. With this technique, it is nearly impossible to scribe straight lines into the grated surface, since the diamond tool is moved in a circular path as it cuts in a typical SPDT system. Regardless, this technique has been shown to pattern reliable, high-efficiency diffraction gratings.

The second technique for fabrication of gratings is among the most well-established methods. Gratings may be made in a photosensitive emulsion with the light from an interferometer. The light of the interferometer is aligned to produce a finely spaced fringe pattern with the desired pitch, and then the photosensitive material is exposed to this pattern, creating a hologram in the emulsion. This hologram now contains the desired fine structure of the grating. It may be chemically processed and reproduced lithographically to create other gratings.

The final technique involves patterning the grating via high-resolution optical or electron-beam lithography (EBL). Careful lithographic processing can create a diffraction grating with square-edge or even blazed (saw-tooth) grooves. This technique provides the best control of the grating groove geometry, and therefore the diffraction efficiency.

An extremely important optical instrument that uses diffraction gratings to split light into its spectrum is known as a *spectrometer*. This instrument is designed to use lenses or mirrors to illuminate a grating that spreads the incident spectrum over a pixel array of detectors. By doing this, each incident color can be registered to a different column of detectors. Spectrometers can be used to study the spectrum of any material that reflects or emits light. A diffraction grating is inspected for quality either via optical or electron-beam microscopy of its surface, or by testing it within a spectrometer.

Absorptive Media

Materials' transmissive and reflective surfaces determine what happens to light's energy as it interacts with an optical surface: optical energy may transmit through or reflect off a surface. Light's energy may also be absorbed by the material into which it is propagating; this property of light-matter interaction is called *absorption*. Absorption is the loss of optical energy as it is converted to thermal energy (heat), optical energy of shorter wavelengths, or even acoustic energy called phonons.

Absorption is a negative aspect of a lens or mirror, but it is desirable to make some parts of a complex, multielement optical system that effectively extinguish or filter particular wavelengths of incident rays of light. A practical example of this is the engineering design of laser goggles. It is undesirable for laser goggles to transmit or reflect the wavelengths from which they are designed to protect the user. Therefore, laser goggles are actually filters made from or coated with absorptive materials at the protecting wavelength.

In many applications, certain surfaces must be extremely absorptive for all wavelengths. These absorptive surfaces may be potential scattering sites or stray light points that must not interfere with the main signal through the optical system. Edges of lenses are often blackened to absorb light that might scatter to its sides. Most metal optical mounts have blackened surfaces. It is important to keep in mind that even though a surface appears to be black when viewed under visible light, it might not be black for ultraviolet or infrared wavelengths. In fact, there are also likely to be a few visible wavelengths that the material does not absorb well. Take caution to make sure that the blacks are truly black for the application wavelengths of the optical system.

Absorptive surfaces may be fabricated using any of the sundry coating techniques described above, or by using a particular paint that has a chemical structure known to absorb many wavelengths. Even reactive surface preparations such as metal anodization can create spectrally absorptive surfaces—this technique is often used to blacken mirror mounts. Most importantly, the bulk material itself may naturally have the desired absorptive properties.

LABORATORIES

Laboratory 1-A
Shadowgraphs for Striae, Cracks, and Inclusions

Theory

Striae are frozen regions of refractive index nonuniformity. Their effect on precision optics is similar to the aberrations caused when looking through an airplane's exhaust. When present in a transmissive optical element, striae can cause a phase shift of the light that passes through it. The end result is that the image through the glass is not as clear as it could be in the absence of striae. This can reduce the performance of an optical system in which measurement of the phase of the light is important. Cracks and inclusions are breaks in the uniformity and continuity of the glass. They cause scattering sites and also interrupt the phase of the light that passes through the glass. All of these flaws should be minimized during fabrication of precision optical elements, and they should be evaluated during quality assurance testing.

An industry-standard technique for assessment of striae and other flaws within the bulk of a transmissive optical element requires the following test setup. Figure 1-28 shows the configuration in which a transmissive piece of glass is being illuminated with a diverging, filtered light source.

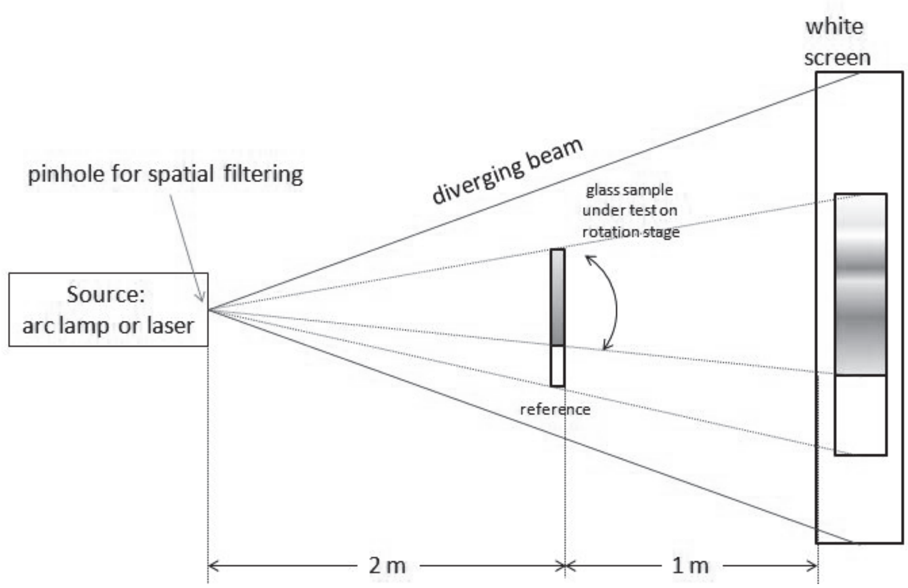


Figure 1-28 *Shadowgraph*

The shadow of the glass is cast onto a white screen or wall, forming a pattern called a *shadowgraph* that indicates the regions where striae, cracks, inclusions, and other flaws are present.

Equipment

- Various optical-grade pieces of sheet glass or plastic (2 or more per group). These should explicitly be made for an optical system, but they can be harvested from unused flat televisions or computer monitors, overhead projectors, high-quality windows, etc.
- Various common pieces of sheet glass or plastic (2 or more per group). These may be cheap photo frame glass or plastic, inexpensive windows, transparent plastic toys, oven glass, etc.
- Optical source options: 100 W mercury arc lamp with aperture (iris), or 5 mW helium-neon laser, diverging via 20x microscope objective and spatially filtered via pinhole.
- A protractor or rotation stage to measure the material's angle with respect to the screen.
- A white screen, large enough to capture the shadowgraph.

Procedure

An industry-standard technique for assessing flaws within the bulk of a transmissive optical element is the shadowgraph technique shown in Figure 1-28. Before the sample is inserted, ensure that the illumination pattern from the source on the screen is uniformly bright. By placing the test sample in the diverging beam, its flaws can be located and measured in shadowgraph.

1. Locate and sketch or photograph the various flaws in each sample when the sample is oriented in a plane parallel to the screen and perpendicular to the source.
2. Assess which material samples are optical-grade materials, and which should not be used in a precision optical system.
3. Slowly rotate the samples to ±2°, ±5°, ±10°, ±30°, and ±45° to better observe the striae and to help determine where features and flaws are located. Surface flaws will appear in shadowgraph, but rotation will help identify the locations of the flaws.
4. Compare your sketches to observations of the glass made by eye. Which flaws were easier to detect by eye (striae, scratches, cracks, inclusions, etc.)? Which required a shadowgraph to observe?

Laboratory 1-B
Coating Check

Theory

Coatings are critical to the performance of precision optics. Coatings may be applied to one or both sides of an optical element. It can be a challenge to determine which side(s) coatings cover, particularly when vastly different types of coating cover each surface. For instance, the front surface of a window may be coated to reflect 50% of green, 532 nm light, while the rear surface is coated to transmit more than 99% of light at this wavelength. Coatings often have a colored appearance, but they may be completely clear. It is a critical technical skill to identify the side(s) on which a precision optic is coated.

Equipment

- 3 to 5 coated optics (e.g., windows, beam splitters, prisms, lenses, etc.)
- 1 or 2 uncoated optics (e.g., windows, beam splitters, prisms, lenses, etc.)
- A bright white incandescent or fluorescent light source
- <1 mW red laser source
- A white screen

Procedure

From the assortment of optics provided, identify the location of the coatings on each optical surface by causing various light sources to reflect from and transmit through the optic. You may use methods such as the spatial-separation technique illustrated in Figure 1-29.

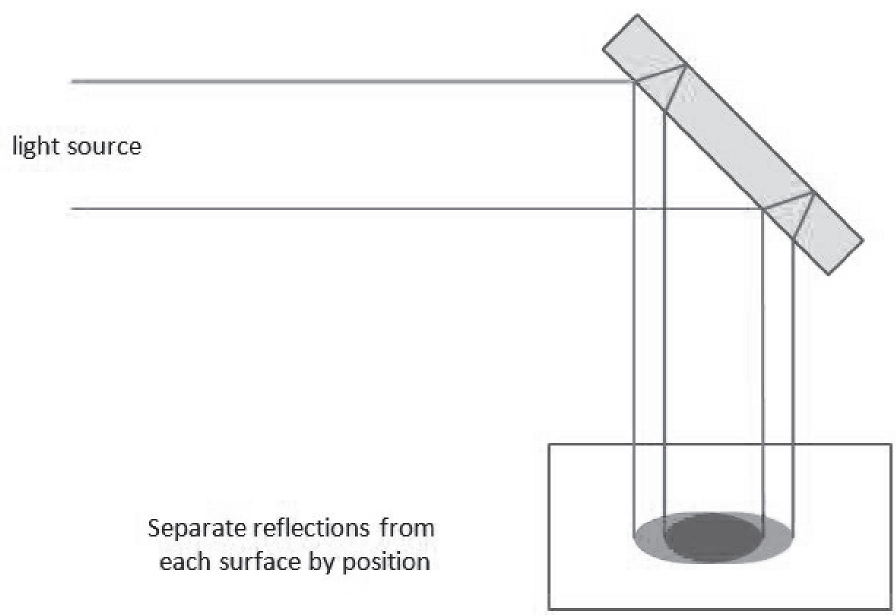


Figure 1-29 *Experiment coatings*

While examining the reflectivity and transmissivity of the samples, estimate the spectral signature of the coatings for light in the visible part of the electromagnetic spectrum. Document your findings in a laboratory notebook and compare your results to the vendor's published data.

Laboratory 1-C
Common Gratings

Theory

The most common gratings are found in optical storage media such as compact discs (CDs), digital versatile discs (DVDs), and BluRay discs (BDs). The data storage density differs among these formats due to the different wavelengths that are used to read and write information on the discs. Shorter wavelengths allow for higher storage density because a smaller optical spot can be focused onto the disc. The data can then be encoded in smaller *pit sizes* with a finer *track pitch* to store more information on the same diameter disc. Pits are the slight depressions or dimples on the surface of the disc that allow a laser to distinguish between digital 1's and 0's. Track pitch is the distance between each track in the disc.

Equipment

- One of each type of optical disc (CD, DVD, BD)
- One HeNe laser, 632.8 nm wavelength

Procedure

Using the diffraction equation, $d \sin \theta = m \lambda$, measure the spacing of the diffracting maximums of the each disc and its track pitch, *d*, using the following method.

By directing a red, 632.8 nm laser onto the surface of each disc at normal incidence, find the first ($m = 1$) diffracted order. Measure the diffracted angle, θ, and use this to calculate the track pitch, *d*, for CDs and DVDs. Compare your results to information published online.

Advanced Procedure

Making measurements for CDs and DVDs should be straightforward, but BDs will require an oblique angle of incidence, which uses the more complicated diffraction equation for oblique incidence, $d(\sin \theta_m + \sin \theta_i) = m \lambda$, in which θ_m is the angle to which the light is diffracted, and θ_i is the angle of incidence. Use any $\theta_m > 45°$ for this experiment. (Note that this equation becomes the regular diffraction equation when $\theta_i = 0°$). Calculate the track spacing, *d*, for BluRay discs.

Explain why red light that enters the BDs at normal incidence does not diffract.

PROBLEM EXERCISES AND QUESTIONS

1. All the following materials are designed to interact with light. Which could be considered precision optics?

a. prescription eyeglasses	h. car rearview mirror	o. diamond earrings
b. magnifying glass	i. coated polarizing sunglasses	p. diode laser collimating lens
c. car windshield	j. wine glass	q. heat-reflecting office windows
d. chandelier crystal	k. children's binoculars	r. telescope eyepiece
e. SLR camera	l. watch cover glass	s. commercial aircraft windows
f. telephoto lens	m. cell phone touch screen window	t. solar panel reflectors
g. bathroom mirror	n. cheap sunglasses	

2. Write a simple flowchart that lists each step in the fabrication of a fused silica glass lens with a standard visible-light antireflective (AR) coating.
3. Write a simple flowchart that lists each step in the fabrication of a nickel-plated aluminum mirror with a high-reflectance (HR) coating.
4. Examine the periodic table of the elements to determine what flint-glass additives to silicon dioxide have in common, and what crown-glass additives have in common. Suggest potential additives to make flint glass and crown glass, in addition to those listed in the text.
5. Describe the difference between amorphous, polycrystalline, and monocrystalline optical materials.
6. A piece of glass is examined by scanning a laser through it to determine the homogeneity (uniformity) of its refractive index. It is determined that there are streaks of inhomogeneity within the bulk of the glass. What are these flaws called? What could have been done during processing to prevent them?
7. A piece of glass is examined by microscope. It is determined that there are air pockets frozen within the bulk of the glass. What are these flaws called? What are some optical effects that result if these remain in the final optic?
8. Describe how the two most common coating processes work and how the optical substrate should be oriented during coating.
9. Preston's material-removal equation includes four variables: C_p, p, v, and t. What do these variables represent? What is the resulting quantity when these variables are multiplied together?
10. Sketch the sag of an American football across the laces from tip to tip.
11. The radius of curvature of the convex side of a planoconvex lens is 200 mm. What is the focal length of this lens?
12. Are magnifying bathroom mirrors concave or convex surfaces? Why?

13. Rainbows can be seen on the back of a compact disc (CD) or digital versatile disc (DVD). What phenomenon is causing this rainbow effect? If a laser illuminates the back of a CD or DVD, will a rainbow be formed? Why or why not?
14. A black-anodized aluminum plate appears very dark under visible illumination. However, when it is viewed with an infrared camera, its surface appears very shiny (reflective). Explain why its absorptivity is different for different wavelengths.

Advanced Problem Exercises and Questions

15. Note that no parameter of Preston's material-removal equation has a greater influence than any other. For example, if the polishing velocity is doubled, that has the same effect as doubling the pressure. Of course, parameters may only be changed within reason. Discuss different reasons why a precision optician might choose to increase one parameter of this equation rather than another. Estimate or research ranges of reasonable values for C_p, p, v, and t. Would any of these parameter ranges change with the size of the optic? Which might change with the optical material?

16. To fabricate and measure any optical element, it is necessary to know how far the surface of the optic deviates from a flat plane. This is called the *surface sag*, and it may be calculated using the following equation. The sag of an optical surface from a plane is given by the variable $z(r)$ as a function of the radial distance r from the optical axis.

$$z_{conic}(r) = \frac{r^2}{R\left(1 + \sqrt{1 - (k+1)\frac{r^2}{R^2}}\right)}$$

The variable R is the surface's spherical radius of curvature, and k is the surface's *conic constant*, the values of which are shown in the table below for the various types of aspheres. (It is important to discern the radial distance from the vertex of the optic, r, from the optic's spherical radius of curvature, R.) The fact that surface sag is based on the spherical radius highlights the fact that aspheres are just slight departures from spheres; however, they can have profound effects on the performance of the optical systems in which they are used.

Conic constants for aspheric optical surfaces

shape	conic constant
$k < -1$	hyperboloid
$k = -1$	paraboloid
$-1 < k < 0$	ellipsoid (major axis of revolution)
$k = 0$	sphere
$k > 0$	ellipsoid (minor axis of revolution)

It is possible to start with a spherical surface, and then turn it into an asphere by removing a small amount of material by polishing or using a diamond-turning technique. If a spherical convex mirror of radius $R = 200$ mm and a clear aperture of CA = 100 mm (r = 50 mm) is to be turned into an ellipsoidal mirror, how much material needs to be removed at the edge of the CA if the conic constant of the ellipsoid is $k = +1$?

17. The sag equation is not a linear equation. Removing 0.5 mm at the edge does not mean that half as much material should be removed halfway to the edge. Prove this for the same 200-mm radius sphere of problem 2.

18. Create a spreadsheet that plots the sag equation for an asphere as a line (scatter) plot. Plot r in the first column and $z(r)$ in the next column. Create a second $z'(r)$ column to plot a different asphere. Compare the differences when using the same radius of curvature (R) for two types of aspheres: a paraboloid with $k = -1$ and a ellipsoid with $k = +1$. Make this spreadsheet modular so that it can be used for an asphere with an arbitrary conic constant, radius of curvature, and clear aperture.

19. This problem involves thermal and mechanical considerations that are typical in optical system design and application. A precision rhomboid is required to translate a beam. The entire optical system before this rhombus is made from BK7 glass mirrors mounted in aluminum mounts. Discuss the differences between choosing a hollow rhombus that is mounted in an aluminum housing versus a solid rhombus made of BK7 glass. If the light were infrared at a wavelength of 5.0 μm, how would that influence your decision?

20. When depositing a coating material by evaporation, the material being deposited, the *evaporant*, must be heated to its boiling temperature and evaporated onto the substrate. Therefore, the material holding the evaporant must be formed into a container that is able to withstand the high boiling temperature of the evaporant. Listed below are the melting and boiling temperatures of materials commonly used for evaporation of optical coatings. Which materials would make good crucibles for a gold evaporant? What about titanium? Silicon? Nickel?

material	melting temperature [°C]	boiling temperature [°C]
aluminum	660	2519
aluminum oxide	2072	2977
amorphous carbon (graphite)	3500	4027
boron nitride	2973	3273
chromium	1907	2671
cobalt	1495	2927
copper	1085	2927
germanium	939	2820
gold	1065	2856
indium	157	2072
magnesium	650	1090
magnesium oxide	2852	3600
molybdenum	2623	4639
nickel	1455	2913
palladium	1555	2963
platinum	1769	3825
silicon	1414	2900
silver	962	2162
tantalum	3017	5458
tin	232	2602
titanium	1668	3287
tungsten	3422	5555
zirconium	1855	4409
zirconium oxide	2715	4300

Sputtering is often performed in the presence of a reactive gas as well as the inert sputtering material. If a silicon target was sputtered to coat a fused silica lens, what material would be coated onto the lens if the reactive gas oxygen (O_2) was injected into the sputtering chamber? What if nitrogen was injected? Argon? Xenon? Fluorine?

21. The phenomenon of diffraction can be explained with a simple equation that can be used to determine how different wavelengths of light, λ, will diffract to different angles θ, depending on the fine spacing or pitch, d, of the diffractive apertures or grooves that comprise a diffraction grating.

$$d \sin\theta = m\,\lambda$$

Constructive interference occurs for light traveling in many directions, and each direction is known as an order, m. If a 693 nm laser passes through a diffraction grating with a spacing of $d = 0.050$ µm, calculate the angle from the central spot to the third order ($m = 3$).

22. A commercial double-axis diffraction grating states that its grooves are formed at 13,500 lines per inch. A laser from a BluRay player is directed through this grating and

onto a wall that is 10 meters away. What is the distance, y, from the central beam to the second-order diffracted beam?

23. Optical storage media include compact discs (CDs), digital versatile discs (DVDs), and BluRay discs (BDs), among other technologies. The data-storage capacity differs among these formats due to the different wavelengths that are used to read and write information on the discs. Shorter wavelengths allow for higher data-storage density because smaller *pit sizes* and a finer *track pitch* cram more information onto the same size (diameter) disc. In fact, the fine track pitches are what cause rainbows to appear on optical discs—the track pitch grooves diffract the room light into its spectrum. The table below shows the read/write wavelengths and track pitches for these three types of optical media.

optical media type	wavelength [nm]	track pitch [μm]
CD	780	1.6
DVD	650	0.74
BD	405	0.32

If a red helium-neon (HeNe) laser illuminates each type of disc, a DVD will diffract the first order of the HeNe light to a larger angle than a CD because a DVD has a finer track pitch. To what angles do each disc diffract the first order of a HeNe laser? Which diffracted order from the CD overlaps the first diffracted order from the DVD? What happens to red HeNe light when it is diffracted by a BD?

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Characterization of Optical Materials and Precision Optics

Module 2

of

Quality Assurance of Precision Optics

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

PREFACE TO MODULE 2

This is the second module in the *Quality Assurance of Precision Optics (QAPO)* course. This course provides an overview of processes used to manufacture precision optics elements; introduces quality assurance (QA) practices required to identify, inspect, and measure optical components; and presents a comprehensive review of measurement practices essential to ensuring the quality of optical components. This course is designed for students seeking a basic understanding of how precision optics components are produced and what techniques are used to validate their adherence to industry standards. This course was designed to comply with the 2nd Edition of the National Precision Optics Skill Standards for Technicians.

Module 2, Characterization of Optical Materials and Precision Optics, addresses the optical parameters and material properties that impact the quality of precision optics. It covers industry specific terms, tools, and techniques used in assessing the quality of precision optics; explains the dimensional parameters and material properties that affect a precision optic's performance; and provides techniques for evaluating optical performance.

The material presented in this module involves technical terms and measurement techniques that are often unique to the field of precision optics. To make certain users have the vocabulary needed to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of this course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary will be italicized throughout the course material.

CONTENTS OF MODULE 2

Module 2
Characterization of Optical Materials and Precision Optics

INTRODUCTION

To assure the quality of a precision optical element, it is essential to understand the optical parameters and material properties that need to be assessed. The way light interacts with each optical element determines the performance of the optical system containing these elements.

This module begins by covering the industry-specific terms, tools, and techniques required for quality assurance of precision optics. This module then explains the dimensional parameters and the material properties required to make a precision optical element, including the ways that an optic interacts with the other components of its optical system and the surrounding environment. Finally, the evaluation of radiometric optical performance is covered in detail.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers*: Modules 1-1, 1-2, 1-4, 1-5
OP-TEC *Quality Assurance of Precision Optics*: Module 1

Students should be able to calculate ratios and angles, apply scientific notation, perform dimensional analyses of units, understand the use of geometric equations to describe conic sections (parabolas, ellipses, etc.), and use trigonometric formulas and algebraic equations.

OBJECTIVES

- Understand the terms associated with measurement and quality assurance, including nominal value, tolerance, absolute, relative, calibrated, precision, and accuracy, among others.
- Understand and use the instruments associated with precision optical measurements, including interferometers, autocollimators, and microscopes, among others.
- Use the tools required to make precision length and distance measurements, such as rulers, calipers, micrometers, gauges, and interferometers.
- Use appropriate hand tools (e.g., calipers, micrometers, depth gauges, spherometers) during fabrication and inspection of optical components.
- Align physical and optical centers following specifications.
- Use the tools required to make precision angle measurements, such as gauge blocks and autocollimators.
- Use autocollimators to measure angular error, beam deviation, and dimensional deviations for both in-process and finished products.
- Use the tools required to make precision measurements of curved surfaces, such as height gauges, test plates, and interferometers.
- Test finished components by appropriate means, including test plate or interferometric techniques, to ensure compliance with design specifications.
- Measure and record dimensionality to ensure adherence to specifications and tolerances.
- Describe the refractive optical properties of materials, including refractive index, dispersion (Abbe number), and birefringence.
- Understand the basic operation of instruments required to measure refractive optical properties of materials, including refractometers, polarimeters, and ellipsometers.
- Inspect materials using birefringence testing via polarimeters and index of refraction testing.
- Describe the radiometric properties of materials, including reflection, transmission, absorption, and emission, as well as the more advanced emitting properties of luminescence, fluorescence, and bi-directional reflectance distribution function (BRDF).
- Understand and use the instruments and techniques associated with precision radiometric measurements, including spectroradiometers/spectrophotometers, spectrometers, and integrating spheres.

SCENARIO

Guido has been working as a service mechanic in a machine shop since high school, but business has been slow lately. His management team decided to rally business by diversifying the company's work, so they sponsored Guido to learn new skills working with precision optics fabrication equipment. While in school, he discovered that many of the new skills and tools he was learning about were similar to those he had been using as a mechanic. This was a great opportunity! He learned that the computerized numerically controlled (CNC) machines, mills, and lathes that he had been servicing for years could be used to make precision optical elements in addition to metal mechanical hardware. He also used familiar tools, such as calipers and gauges, to develop hands-on experience with optical elements. He now understood how the operation of mechanical systems applied to the exacting demands of precision optics fabrication. As a result, Guido's company was able to form cooperative relationships with precision optics vendors around the world, and business improved. Later on, Guido's schoolwork and experiences with complex machinery afforded him a side job with one of the local precision optics manufacturers, where he worked to fine-tune the operation of their CNC machines and water-jet mills.

BASIC CONCEPTS

Quality Assurance Terms and Techniques Used for Evaluation of Precision Optics

The first step in gaining knowledge of any technical field is learning the terms and basic scientific concepts. If you can speak the language of a technical field and understand how science enables its processes and procedures, then you have the tools needed to develop expertise in this field.

Terms Associated with General Technical Measurements

This module details the many measurements required in precision optics. In this case, a measurement is a *quantitative* evaluation of a precision optic's specific numeric property. It is not enough to say that a lens coating transmits green light and reflects red light. It may be necessary to ensure that, for example, a lens coating transmits greater than 90% of green light at a wavelength from 512 to 565 nm, and reflects greater than 70% of red light from 610 to 750 nm. Quantitative measurements of precision optics will reveal these specific properties after an optical element has been precisely fabricated.

It is important to recognize that some tools and instruments make *relative* measurements of properties. In relative measurements, two similar samples are compared and the results are reported as a ratio. For example, the diameter of a mirror with serial number 4 is 1.03 times the diameter of a mirror with serial number 2.

Absolute measurements are conducted with respect to a reference that has been *calibrated* to a known quantity or standard. Absolute measurements are superior, but might not always be practical. To make most absolute measurements, test equipment should be calibrated to an industrially accepted standard. Most precision optics shops regularly calibrate their measurement tooling and equipment.

All dimensions and properties of a precision optical element will be written or *specified* on a drawing along with a *tolerance* for each dimension or property. Tolerance is the set limit or limits of a physical dimension. For example, an optical window might be specified to have a thickness of 7.000 ± 0.030 mm, where "7.000 mm" is the *nominal specification*, and "0.030 mm" is the tolerance on that specification. The limits or "tightness" of the tolerance associated with each feature of a precision optic usually depend on whether the feature interacts with light. For example, the surface of a lens receives a full beam of light, but the bevel of a lens edge only interfaces with a mechanical mount. Therefore, the tolerances of features that form a lens's face (the optical surface) are usually much tighter than the tolerances of peripheral specifications, such as mechanical features or electrical properties. However, if mechanical features help to locate a precision optical element within its mount to an optical beam, the peripheral mechanical tolerances may be very tight as well.

A basic understanding of two (frequently misused) words is required when evaluating precision optics. The term *accuracy* refers to making an optic's feature equal one particular absolute value. The term *precision* refers to accurately making many copies of a part with features within a tight tolerance around the nominal specification—this is why the tolerance specification is critical. For example, a lens diameter may be specified on a drawing as 50.000 ± 0.050 mm. If a set of ten similar lenses are made with diameters of 45.000 ± 0.001 mm, they are inaccurate, but high precision. Conversely, a set of lenses made with diameters equal to 50.000 ± 0.500 mm may be considered accurate, but they have low precision.

As a rule of thumb for measurement accuracy, the tool used to make the measurement should have a *resolution* (that is, minimum-resolvable increment) better than ten times the tolerance required by the drawing specification. For example, if a part has a required diameter of 50.000 ± 0.001 mm, then the scale used to measure that diameter should be calibrated to accurately report values with a resolution better than ±0.0001 mm.

Terms Associated with Optical Measurements

Nearly all optical properties associated with precision optics are *spectral quantities*—properties that depend on the color of the light used in testing or applying optics in specific applications. For instance, just because a material reflects green light from a mercury-vapor discharge lamp at 546.1 nm, that does not mean it will reflect an equal amount of green light from a frequency-doubled Nd:YAG laser at 532 nm. Every optical material has a characteristic *spectral signature*, in that it will interact with every color of light in a unique way.

Many optical properties are also *polarization dependent*, in that their interaction with light depends on the direction of the light's electric field vibration relative to the light's incidence direction on the optical surface. Polarization states are described as *p-* and *s-polarized* light, depending on whether the light is vibrating parallel to (within) the plane of incidence or perpendicular to the plane of incidence, respectively, as illustrated in the Figure 2-1. It is critical to recognize that more s-polarized light is reflected by a material than is p-polarized light, especially at larger angles of incidence.

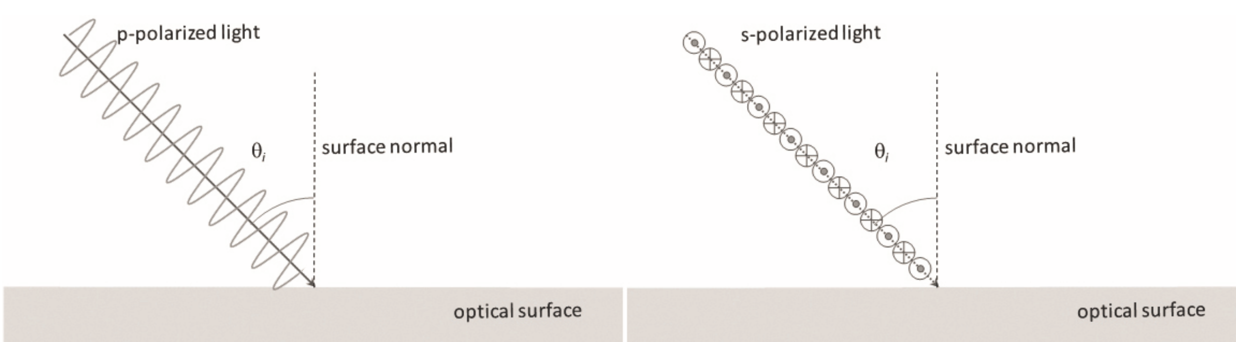


Figure 2-1 *This illustration differentiates p-polarized light (left figure) from s-polarized light (right figure). In each case, the angle of incidence is given by the parameter θ_i. It is simple to represent p-polarized light vibrating in the plane of the page as a wave, but s-polarized light vibrates in and out of the page, so it is represented by arrowheads ⊙ and arrowtails ⊗.*

The *optical surface* of a precision optic is the surface that is designed to interact with light. It has two basic characteristics, a *size* and a *shape*. The *size* or lateral extent of a precision optical element is known as its *clear aperture* (CA) or the *effective diameter*, denoted ϕ_e per the ISO 10110 optical drawing standard. The CA defines the optically active region of the precision optic within its diameter, usually measuring slightly less than (about 90%) its physical diameter.

The optically active region is that part of the precision optic that interacts with the light. The CA is a necessary and important parameter to specify because optic mounts typically obscure part of the outer diameter anyway, and the CA allows the fabrication shop freedom when making the optic—the part does not have to be precision all the way to its edge. Coatings may be applied in areas larger than the CA, since the edges of coatings are seldom uniform. Tooling and handling features may interface with the optic within its diameter, but must stay outside its CA. Quality of an optical surface outside its CA is governed by the standard used to fabricate the part.

The *shape* of a precision optical element is known as its *surface figure*. This is the contour of the optical surface, a three-dimensional topography of the surface that captures the highs and lows, the hills and valleys within the CA. The surface figure is a critical parameter to evaluate for an optical element. In fact, it is often the tight tolerance of the surface figure that distinguishes a precision optical element from a common piece of glass.

If the surface figure of a precision optic is curved, it will refract or reflect light incident on it to one point. This is known as the *focal point*. An approximate distance between the optic and the focal point is known as the *focal length*. This value will be an explicit part of most optical designs (even flat optics have a focal length equal to infinity), and it may need to be measured to a tight tolerance. Another important optical parameter is the *f-number*. This is simply the ratio of the focal length to the clear aperture. Some optical designs may specify an f-number (or a range of f-numbers for a zoom system), rather than a focal length.

Tools and Techniques Used to Measure Precision Optics

When making certain optical measurements of a precision optical element, it is common to test *witness samples* rather than the element itself. During fabrication, in addition to the precision optic itself, a number of small, flat windows or mirrors are made. These witness samples are made of the same material, undergo similar processing (e.g., grinding, polishing, cleaning), and have identical coatings as the precision optic. They are created to represent the optical and spectral properties of the precision optic and to ensure safety in handling the final (usually expensive) precision optic. Witness samples are typically made as flat, 1" diameter windows that fit in the beam paths of the measurement systems.

When making measurements, the beam of light used to test the witness samples is from a laser or another *collimated* source. A collimated beam propagates in a straight line that does not significantly diverge or converge. This simplifies the test setup because the direction of the source is well known and predictable. A related term, *optical infinity*, is important to understand when testing optical systems. *Optical infinity* conveys a very long distance between the object being imaged and the optical system (or between the image produced by an optical system and the system itself). For most practical systems, a few tens of meters is a sufficient distance to approximate optical infinity. Just as all materials have a surface shape, a beam of light has a shape as it moves through space. This is known as the *wavefront* of the light, which is directly related to the light wave's phase across the beam. In general, an ideally collimated beam will have a flat wavefront, and a converging or diverging beam will have a spherical wavefront.

In addition to a laser, a common test tool that uses a collimated beam is an *autocollimating alignment telescope* (or simply an *autocollimator*). This telescope is used to conduct many different types of optical tests and precision alignments, but its operational use for all test configurations is similar. The autocollimator is aligned to the surface(s) being measured, and it projects an image of its *reticle* (an internal, calibrated crosshair) toward the surface(s), thereby sending collimated light toward the surface(s) being tested. The telescope can focus on any of the intermediate surfaces to aid with alignment. If light is reflected from the test surface(s) back into the telescope, then the reticle can be used to measure the angular deviation between the telescope's line of sight and the reflected image of the reticle.

Because precision optics have spectral and polarization-dependent properties, they require *optical sources* with many different wavelengths and polarization characteristics. To create many wavelengths, a broadband light source, such as an incandescent filament or another thermal source, can be split into its constituent colors using a *monochromator*. This instrument either diffracts the source light into its spectrum using a grating or disperses the light into its spectrum using a prism. Often in testing precision optics, each color is sequentially directed onto the witness sample associated with the precision optic being tested. After light interacts with the witness sample, the optical signal must be measured by a *detector*. The detector material and technique depend on the wavelength(s) being measured. Common detectors are silicon, Si, (for wavelengths in the 200 to 1100 nm spectral region); indium gallium arsenide, InGaAs, (700 to 1800 nm); germanium, Ge, (800 to 1700 nm); indium antimonide, InSb, (1500 to 5000 nm); mercury cadmium telluride, HgCdTe, (1000 to 26000 nm); and deuterated triglycine sulfate, DTGS, or deuterated L-alanine-doped triglycine sulfate, DLaTGS, (2000 to 22000 nm).

To create different polarization states, technicians use *linear polarizers* and *waveplates*. These devices only transmit light with certain polarization states, creating light of pure, known polarization. *Polarimetry* is the analysis of light's polarization state before and after it interacts with an optical material. When polarimetry is used to measure thin film coatings, it is known as *ellipsometry*. Both ellipsometers and polarimeters illuminate a sample of the material to be tested with light of a known polarization state. The transmitted or reflected light then passes through a polarizer called an *analyzer* before it is collected on a detector and analyzed. These techniques measure the amount of light in each linear polarization state—that is, the amount of s- and p-polarized light. This system gives the polarization properties of the coated optical element.

Spectrometry is the measure of the quantity of light at each wavelength before and after it interacts with an optical material. Basically, at each wavelength, the power of light is measured once as it leaves a source, and again after it interacts with a witness sample associated with a specific precision optic. This test reveals the *radiometric properties* of the optical element and its coating.

Interferometry represents a broad field of measurement techniques that are critical to optical testing. The basic principle of interferometry involves causing two beams of coherent light to overlap. When two coherent beams overlap, they superpose, creating an *interference pattern* or *interferogram* made up of bright and dark bands called *fringes*. These fringes are the result of the superposition of the two wavefronts. Bright fringes are created where the two wavefronts are in phase, and dark fringes where the two wavefronts are out of phase. Fringes appear across the entire clear aperture being measured. The size, orientation, and structure of the fringes reveal the relationship between the wavefronts of the two beams, and therefore the *surface figure* or the *wavefront error* (*WFE*) of the optical element being tested.

If one of the beams in an interferometer is an ideal, collimated beam, it has a flat wavefront, so the resulting interferogram represents simply the wavefront of the second beam. This is the most common application of interferometry in optical measurement: an ideal, flat reference beam with a flat wavefront is split into two beams. One beam is perfectly returned to the interference plane (usually a camera's focal plane), and the second beam is *aberrated* when it interfaces with the optical element being tested. *Aberrations* are changes to the wavefront caused by imperfections in the optical surface(s) being tested. When aberrations can be observed by interferometry, they can be located, measured, and even corrected by polishing.

Many types of interferometers exist, but the most important to optical measurements are called Newton, Fizeau, Michelson, Twyman-Green, and distance-measuring interferometers. They each represent different test configurations, some of which will be covered in the laboratories of this module. Fizeau interferometers tend to be compact and are the most efficient for measuring optical aberrations, because the two beams travel in the same direction. Michelson and Twyman-Green direct each beam in a different direction before recombining them to interfere. These types of interferometers are used when one of the beams needs to be deliberately shifted in phase. Distance-measuring interferometers (DMIs) measure distance using two beams with flat, perfect wavefronts that are tilted with respect to each other. When they interfere, they create straight-line fringes. As one beam propagates, distance is measured by counting the fringes. Since fringes are due to the phase difference between the two beams, the general DMI fringe pattern will remain the same as a beam travels over a distance, but these fringes will scroll across the detector as one beam moves in and out of phase with the other.

All of these terms, tools and techniques are fundamental to testing precision optical elements. The specifics of the parameters and properties that need to be tested and characterized will be covered in the following sections.

Dimensional Parameters of Precision Optics

A number of basic physical parameters need to be precisely measured to ensure that a precision optic has been fabricated to the size and shape specified on its design drawing. Most optical elements are essentially cylinders with contours on their circular faces, but many different sizes, shapes, and additional features may be required. Precision optics need to be made precisely because they interact with light, so many of their dimensions must satisfy the tight tolerances specified by their users. This makes precision optics fabrication one of the most challenging fields of industrial manufacturing.

There are three basic dimensional qualities associated with physical features of precision optics: lengths, angles, and curves. Each quality is measured in a unique way, as described here.

Length Features of Precision Optics

Fabrication systems cut optics into specified lengths using linear guides or encoders. During quality assurance, precision optics are measured with scales (rulers), *calipers*, *micrometers*, or *height* and *depth gauges* relative to a flat, *granite-slab workbench*, as shown in Figures 2-2, 2-3, 2-4 and 2-5. Most tools used to make length measurements are accurate to tens of micrometers or a few thousands of an inch. (One thousandth of an inch, often referred to as "one thou" or "one mil," equals 25.4 μm.) For extremely precise length measurement, a technician may use optical tools such as distance-measuring interferometers (DMIs). DMIs may be accurate to better than a micrometer, depending on the environment in which they are used.

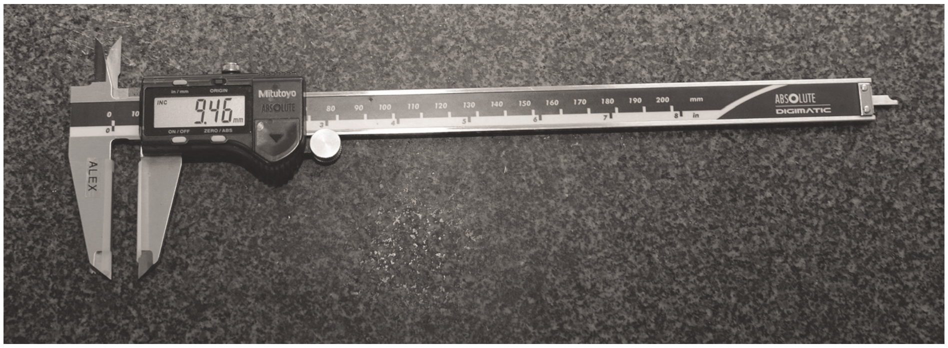


Figure 2-2 *Digital calipers on a granite-slab workbench*

Figure 2-3 *This precision optics technician is using a micrometer to measure the diameter of a precision retroreflector*

Figure 2-4 *A digital height gauge measures precision prisms relative to a flat granite-slab workbench*

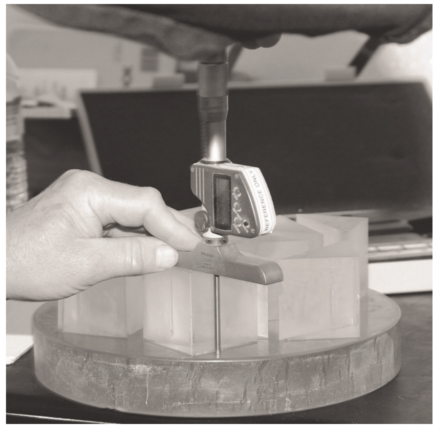


Figure 2-5 *A precision optics technician uses a manual height gauge to measure prisms' lengths*

These length-measuring tools are used to measure the basic features of a precision optical element, including: lens *outer diameter*, *inner diameters of annular optics*, *clear apertures*, *center thickness*, *edge thickness*, and *chamfer size*. Figure 2-6 shows a cross section of an annular optic with its many types of length features indicated.

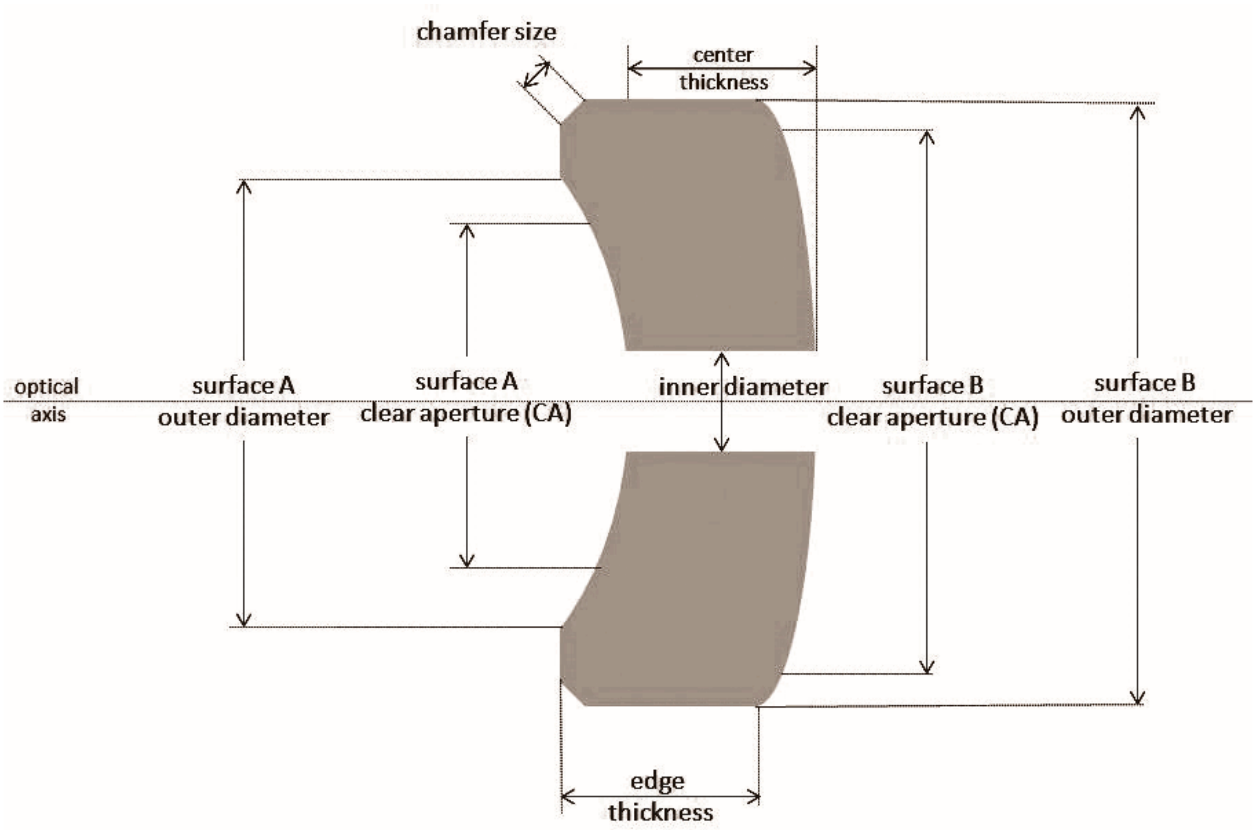


Figure 2-6 *Length features of a cross section of a precision optic*

Angular Features of Precision Optics

Like length features, angle features of precision optics are initially cut using angular guides or encoders within the fabrication systems. During quality assurance, they are measured using *angle gauge blocks*, *calibrated flats* with lasers, interferometers, or autocollimators. Like length features, angular features that interact with light—the *optical angle features*—will be made more precisely than mechanical angle features such as flats, facets, slots, *edge chamfers* and *bevels*. Optical angle features usually refer to the orientation of one surface relative to another. Angular features are inherent to the operation of the precision optic itself. This is obvious with prisms, but in fact, all lenses and mirrors must be made with edges that make exact angles with respect to their optical surface. If these angles are not exact, the precision optic will not perform as designed. For instance in, Figure 2-7, the angle at the top of the lens is not 90°, which will result in *tilt* and misalignment of the optical axis.

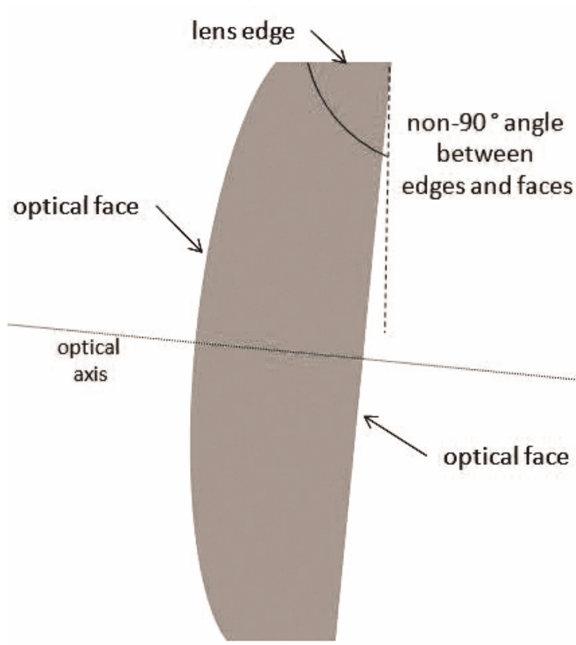


Figure 2-7 *Lens tilt, exaggerated, due to improper edging relative to the optical faces*

Any angle between one optical surface and the other is known as *wedge*. Wedge is a deliberate aspect of an optical design, particularly in windows and beamsplitters, to prevent reflections from both surfaces that travel at the exact same angles. The unintended reflection is known as a "ghost reflection." Wedge must be controlled during fabrication and measured during quality assurance. Figure 2-7 shows light reflecting from two beamsplitters, one without and one with a proper amount of wedge.

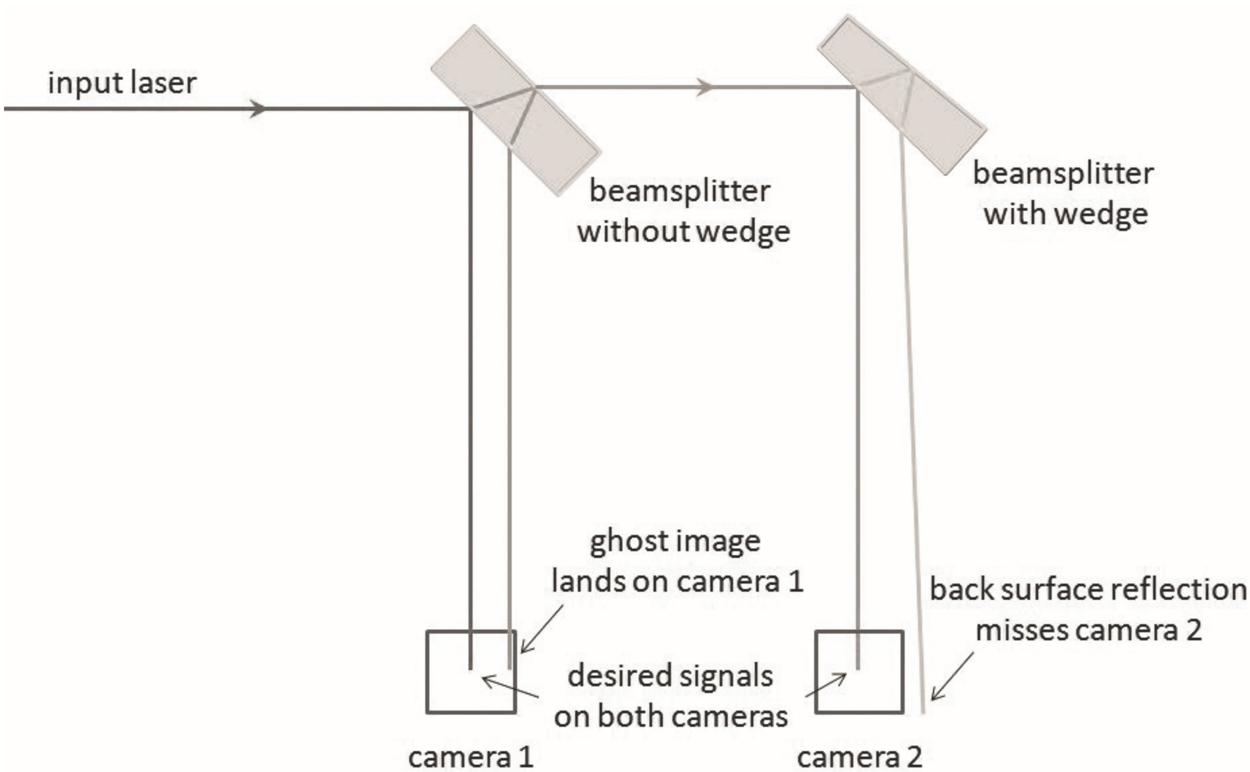


Figure 2-8 *Two beamsplitters, one with and one without wedge. The laser that reflects from the back surface of the beamsplitter without wedge creates a ghost image on camera 1, while the reflection from the back surface of the beamsplitter with wedge misses camera 2 completely*

Most angle measurements are conducted in essentially the same way: Light reflects from a reference surface and from the optic being measured, and the deviation between the two measurements determines the angle. The reference surface for an angle measurement is typically an angle gauge block that has been machined to an exact angle measurement.

Alternatively, as Figure 2-9 illustrates, technicians can use an autocollimator to measure an angle on a precision optic. Figure 2-10 shows a schematic of how an autocollimator measure the angles of a prism. The lines represent the autocollimator's projected reticle and the return images of these reticles—one from the prism surface and the other from the reference flat. Figure 2-11 illustrates these two reticles along with the crosshairs of the autocollimator. If the two images of the reticle lie directly on top of each other, than the lower left corner of the prism is exactly 90°. Figure 2-11 indicates that the lower left angle of the prism is not exactly 90°. The deviation from 90° can be determined from the relative positions of the two reticle images and the autocollimator's crosshairs.

Figure 2-9 *A precision optics technician uses an autocollimator to measure the angular deviation of a prism during final polishing*

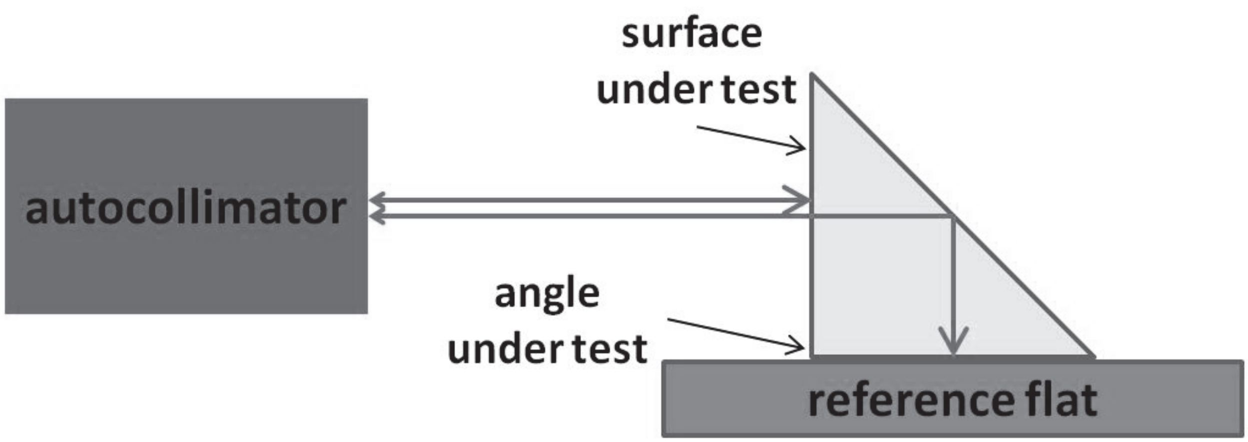


Figure 2-10 *Schematic of a prism angle measurement*

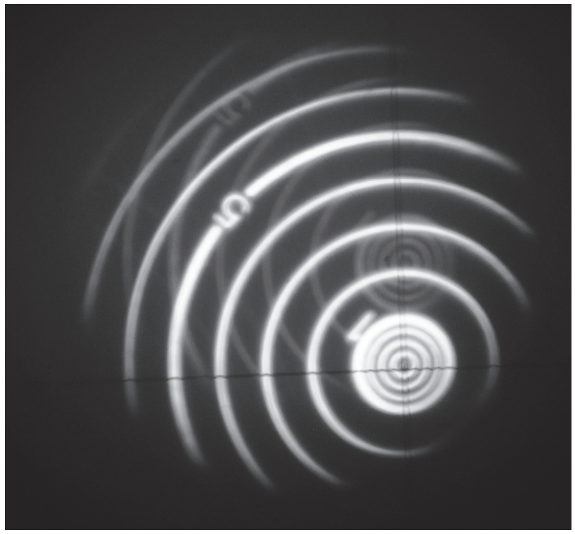


Figure 2-11 *Technicians use the reticle and crosshairs of an autocollimator to determine a prism's angular features*

Curved Features of Precision Optics

Many types of curved features are present on precision optics. The curves of superficial mechanical features such as *edge radii* are measured using gauges or encoders in a manner similar to the measurement of length features. However, more critical curved features require more sophisticated measuring techniques. For instance, an important, high-tolerance curve is the curve of the outer cylinder of an optic, particularly its location with respect to its center, the *vertex* of the optic. This is called the *centration* of the optic and is illustrated in Figure 2-12.

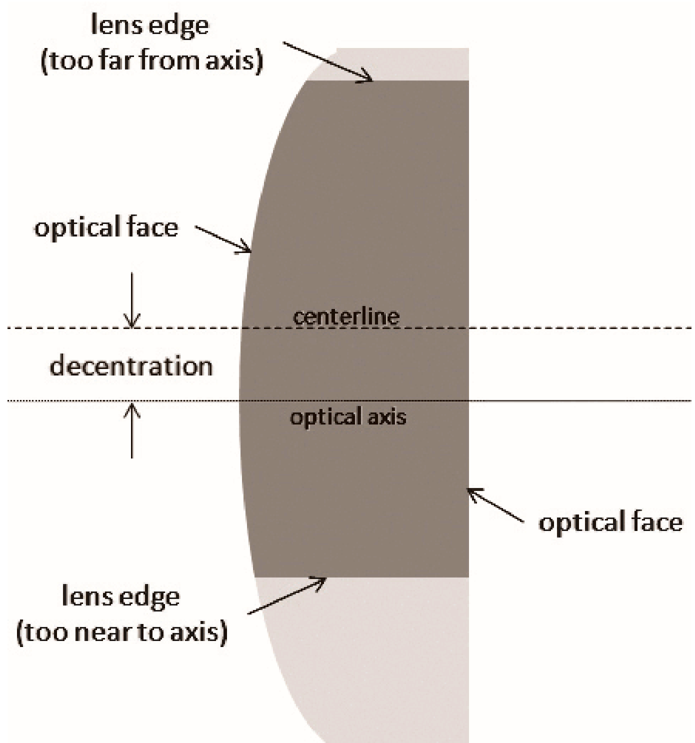


Figure 2-12 *Vertical centration of an optic*

Lens or mirror centering is often measured using a depth gauge to provide a parameter called *total indicated runout* (TIR). This technique, shown in Figure 2-13, requires the part to be rotated about its vertex in a machine like a lathe while a depth gauge contacts its edge. As the part is rotated, the gauge deflects to give a TIR value.

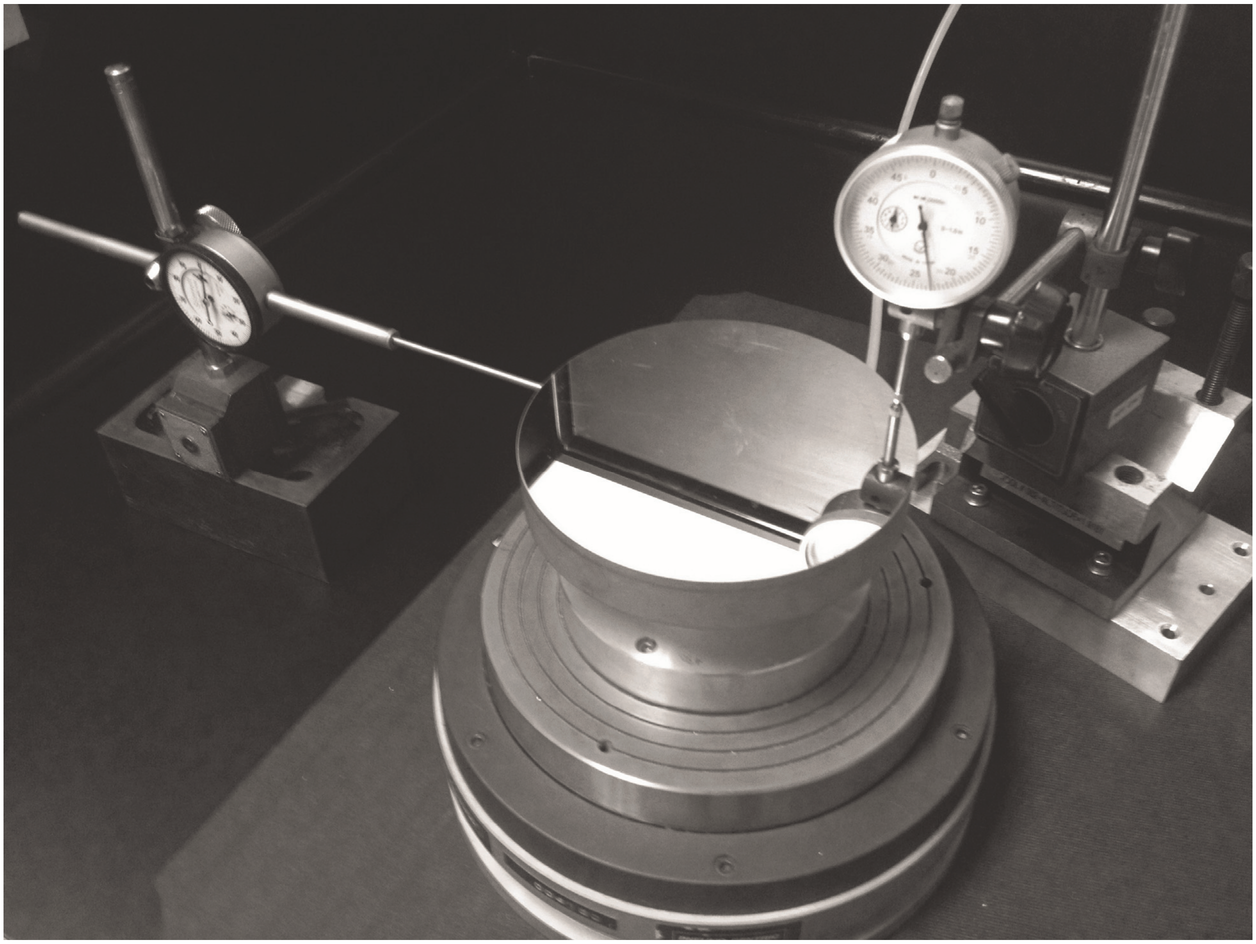


Figure 2-13 *In this total indicated runout (TIR) measurement setup, the gauge on the left measures TIR along the edge of the part, and the height gauge on the right ensures that the optical surface of the precision optical element remains in the same plane as it is rotated*

The most essential curved feature is the optical surface itself—the surface that directly transmits or reflects light. The shape of this surface is given by a *radius of curvature*, *R*. Note that this radius is a spherical or cylindrical radius, so this parameter only directly applies to spherical or cylindrical optics. Most aspheres are described by the radius of their best-fit spheres. An asphere is often first made as a sphere with the radius that most closely matches its aspherical shape.

A variety of techniques may be used to measure spherical or cylindrical radii. A simple mechanical method is to probe the optical surface at four points using a micrometer-like device called a *spherometer*. This tool has three sharp metal tips that form the corners of an equilateral triangle. These three tips are placed onto a spherical optical surface, and a fourth tip, located in the center of the other three, is then adjusted to contact the optical surface. The movable shaft of the fourth tip is calibrated to give the radius of the optical surface. It is common for precision optics technicians to use this tool for a quick radius measurement, but it must be used carefully since it may contact the optical surface directly.

A traditional method of radius measurement compares the optic being tested to a calibrated reference known as a *test plate*, which is a master surface for each radius. This can be a cumbersome and costly process, since it requires a large quantity of calibrated test plates to be kept in inventory and maintained at every fabrication shop. A test plate uses basic Newton interferometry to evaluate surfaces. When the test plate and the optic being tested are aligned, Newton's fringes form due to the phase difference induced by the tiny gap between the test plate and optic. Circular fringes indicate the deviation of the test optic from the reference test plate. Linear fringes simply represent a misalignment in tilt between the test plate and the optic being tested. When the optic matches the test piece, a single fringe will form, indicating that the shape of the optic matches the test plate shape. Fewer circular fringes indicate that the part more closely matches the radius of the test plate. Flat optics are also made and tested in this manner. In Figure 2-14, a flat window is being compared to a flat test plate.

Figure 2-14 *The bottom surface of a flat window (top optic) is tested against a flat test plate (bottom optic, top surface) under narrowband light. Linear Newton's fringes indicate that there is little curve to the flat surface. In the left figure, there are about ten tilt fringes across the window. When the precision optics technician pushes gently on the window, many more tilt fringes result. The presence of only straight fringes indicates that this part is quite flat with respect to the test plate. (Precision Optical)*

As Module 1 explained, an optic's radius equals one-half the surface's focal length. Alternative measurement techniques take advantage of this fact: a radius may be measured optically by directing collimated light onto the surface, which then forms a focal point after it transmits through or reflects from the optic. However, this quick technique is inexact because it requires the technician to estimate exactly where the light will focus, and because for most lenses, it measures the effect of the combined radii of two surfaces, not one. A complete wavefront measurement is required for a high-precision single-surface radius evaluation. To measure the radius accurately, commercial interferometers use a *radius slide* and a DMI as illustrated in Figure 2-15. Using this technique, two interferometer measurements are taken: (1) a standard surface-figure measurement (as covered in the last section of this module) and (2) a measurement with the part aligned so that the focal point of the interferometer is located exactly on the surface being measured (a position known as the "cat's eye" focus). When measured at each position, the optic's mount is located against an extremely straight guide rail so that the DMI beam properly interfaces with the optic (or its mount). The difference between these two measurements, as measured by the DMI, yields a precise value for the surface radius.

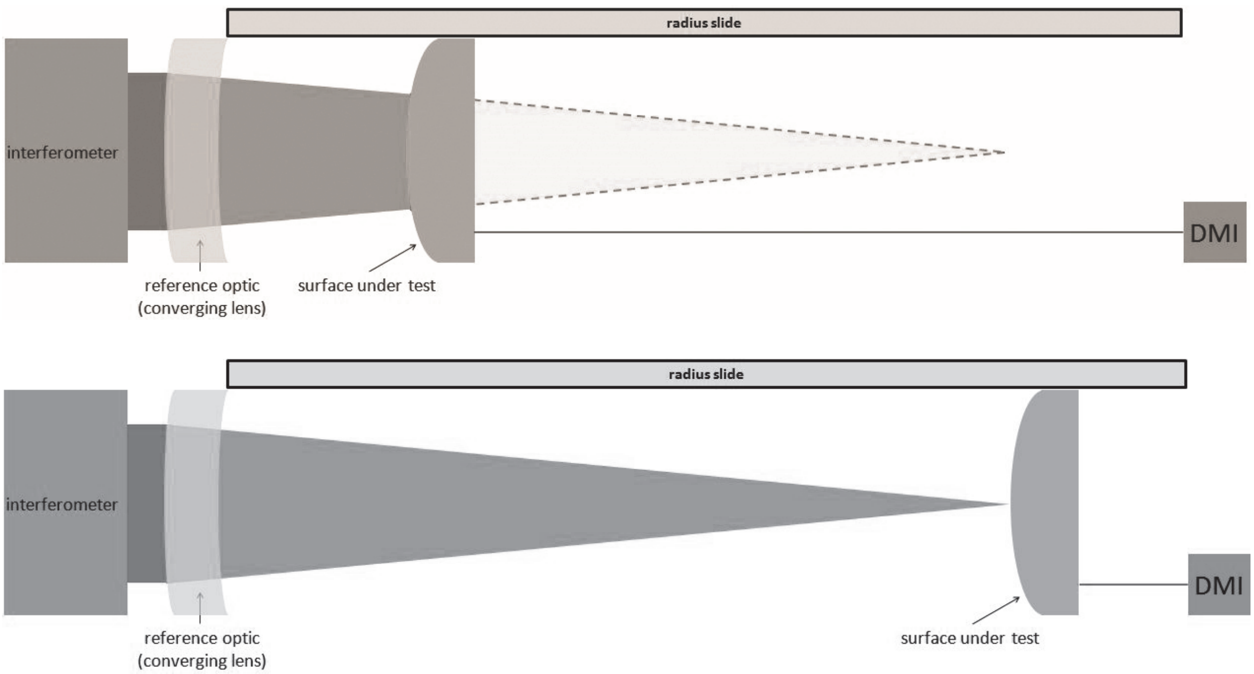


Figure 2-15 *The surface being tested is moved along an extremely straight radius slide from the position at which its surface figure is measured (top) to the position of "cat's eye" focus, at which point its (virtual) focal point is located directly on the surface under test. The radius is equal to the distance between these two positions. To accurately measure this distance, the technician reflects a thin laser beam from a DMI off the optic's mount.*

Optical Material Properties

Light interacts with different materials in different ways. This section covers the optical and physical material properties that guide interactions between light and matter.

Fundamental Glass Parameters: Refraction and Dispersion

Light is known to travel at a constant speed of $c = 2.9979 \cdot 10^8$ meters per second in a vacuum. The phrase "in a vacuum" is critical here, because it correctly implies that light travels at different speeds in other media, such as air and glass. The speed of light in any other material besides a vacuum is reduced by a parameter known as the material's *refractive index*. In general, the magnitude of refraction is related to the type and quantity of particles that interact with the light. In a vacuum, there is nothing for the light to interact with—the absence of materials is the definition of a vacuum. However, as light travels through air, optical materials, semiconductors, dielectrics, and metals, it interacts with the atoms and molecules that form these substances. When a wavefront of light is incident on a material, it changes speed, and therefore it changes direction, or *refracts*, as it moves from one medium to the next.

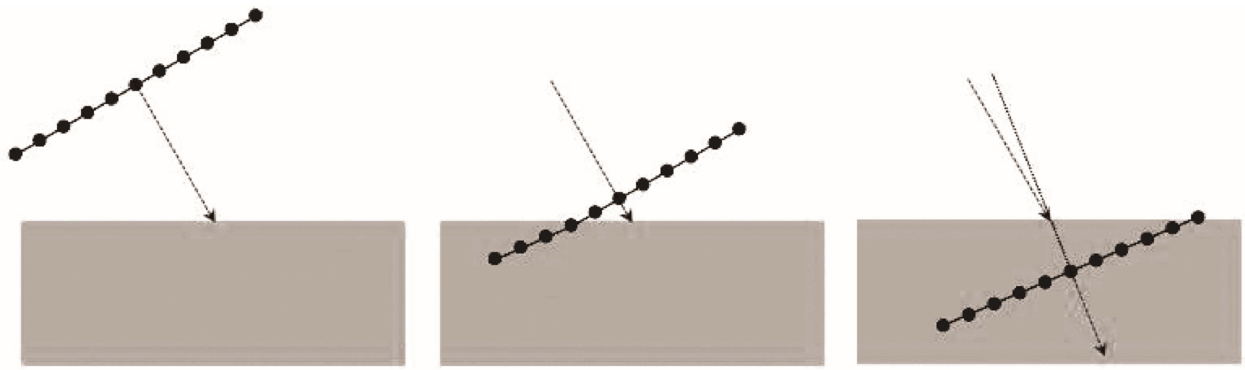


Figure 2-16 *As a wavefront of light (represented by the row of dots) approaches a material along a path (the dashed line), the light refracts. That is, its direction bends because the side of the wavefront that enters the material first is slowed down. The image on the right shows the difference in direction before (incident) and after (refracted) the wavefront enters the material.*

In addition to this effect, every wavelength of light will be refracted by a different amount in every material, making the refractive index a spectral quantity. Light's speed in a material is given by the following equation:

$$v(\lambda) = \frac{c}{n(\lambda)} \tag{2-1}$$

It is not useful or practical to measure light's speed, $v(\lambda)$, in a material. However, it is essential to know the spectral refractive index of the material, $n(\lambda)$. The optical designer uses the refractive index to make detailed calculations about the way that a transmissive optical element bends light.

Designers also need to determine a precision optic's *dispersion*, which describes the dependence of the refractive index on wavelength. The parameter that characterizes dispersion is the glass's *Abbe number*. The standard definition of the Abbe number uses the refractive indexes at three wavelengths in the visible spectrum:

- the refractive index at a wavelength of 587.56 nm (a yellow color made by exciting helium, known as its d-line), written as n_d,
- the refractive index at 486.13 nm (hydrogen's blue F-line), written as n_F, and
- the refractive index at 656.27 nm (hydrogen's red C-line), written as n_C.

The Abbe number is calculated per industrial standard ISO 7944 as:

$$V_d = \frac{n_d - 1}{n_F - n_C} \tag{2-2}$$

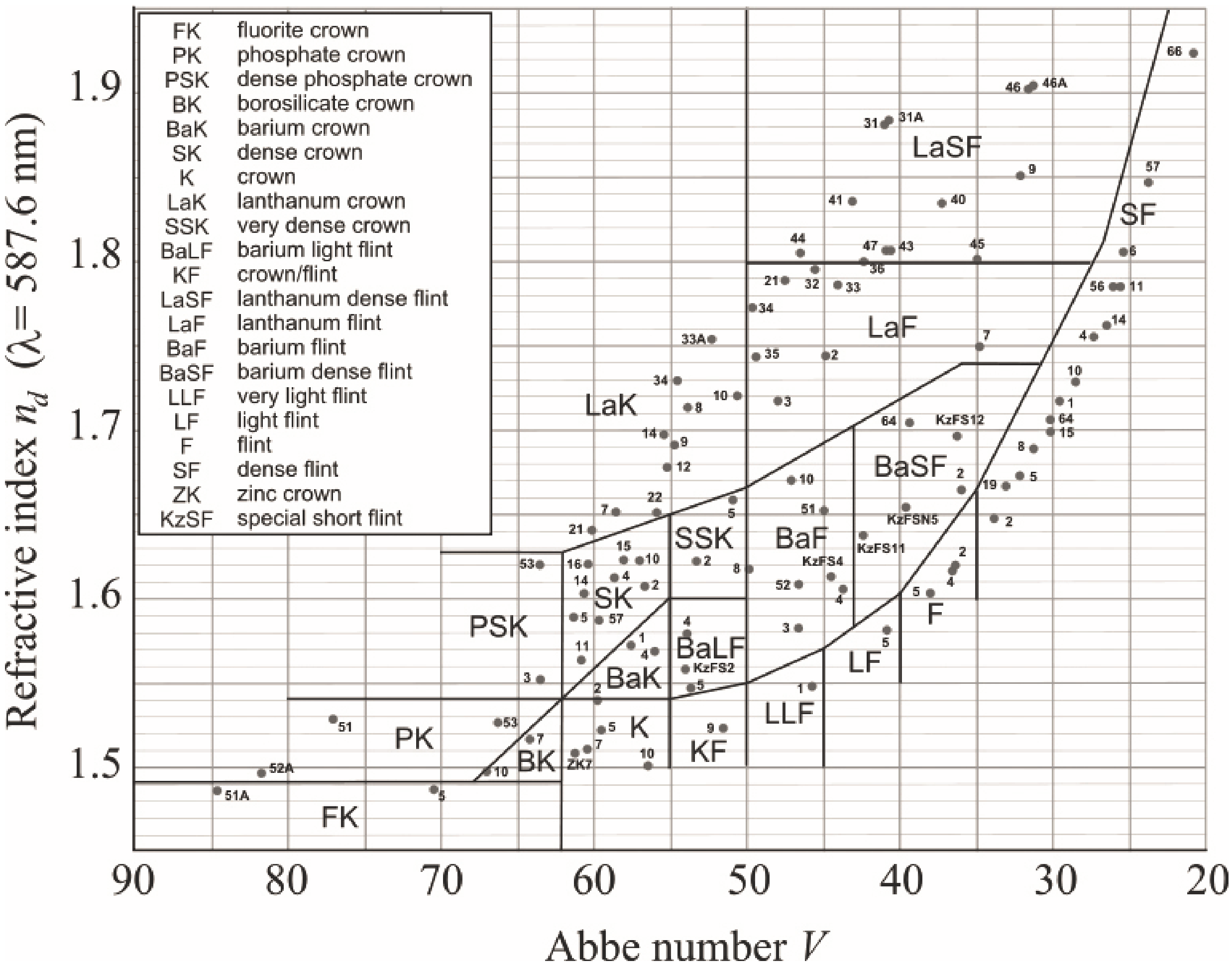
The refractive index of a material has to be measured for every wavelength used in the optical application. For common glasses, such measurements are well cataloged.

The Abbe number is a useful quantity when specifying optics for visible-light transmitting systems. However, infrared materials do not transmit the wavelengths that define the Abbe number. Often, specific Abbe numbers will be fabricated for certain spectral bands using relevant wavelengths. For instance, near-infrared (NIR) performance may be specified with

Abbe numbers based on wavelengths of the spectral band between 750 and 1400 nm, or midwave infrared (MWIR) materials for wavelengths between 3 and 5 µm.

Table 1 shows a dispersion map of the many types of glass available just from the glass manufacturer Schott. This map plots two defining optical properties of glass: the refractive index and the Abbe number.

Table 1 *Dispersion map for Schott glass*



As the plot shows, typical values of a refractive index range from 1.5 to 2.0. (Keep in mind that a refractive index may be as high as 4.0 for some infrared materials.) Typical values of an Abbe number range from 20 to 90 for materials that transmit visible light. In practice, manufacturers use a contracted parameter to classify glasses. This parameter is known as the *glass code*, and it is based on U.S. military standard MIL-G-174, a standard often specified on manufacturing drawings.

A phenomenon called *birefringence* characterizes crystalline and some plastic optical materials. In birefringence, the refractive index depends on the direction from which the light enters the crystal and on the light's polarization. The reason for this effect may be envisioned by picturing an amorphous material and a crystalline material side by side. No matter what direction you look at the amorphous material, its particles look randomly distributed and equally dense. However, if you look at a crystalline material, the particles may be more tightly packed from one perspective than from another. Most optical crystals have two refractive indexes, known as the *ordinary refractive index, n_o,* and the *extraordinary refractive index, n_e*. Their difference defines their birefringence:

$$\Delta n = n_e - n_o \tag{2-3}$$

All forms of sapphire (Al_2O_3), most plastics, calcite ($CaCO_3$), lithium niobate ($LiNbO_2$), and even quartz (SiO_2), among all other crystalline optics, exhibit some degree of birefringence. It is critical to understand the orientation of the crystal matrix when making a cut during fabrication of the crystalline optic and during metrology of its refractive properties. Birefringence values in common optical crystals range from 0.001 (for sapphire) to 0.085 (for lithium niobate).

Measurement of Glass Parameters

So how can these fundamental glass parameters be measured? When light enters a material at a specific incidence angle, the path of the light will be bent due to the material's refractive index. The equation used to calculate the amount of bending is called *Snell's Law*:

$$n_1(\lambda) \sin \theta_1 = n_2(\lambda) \sin \theta_2 \tag{2-4}$$

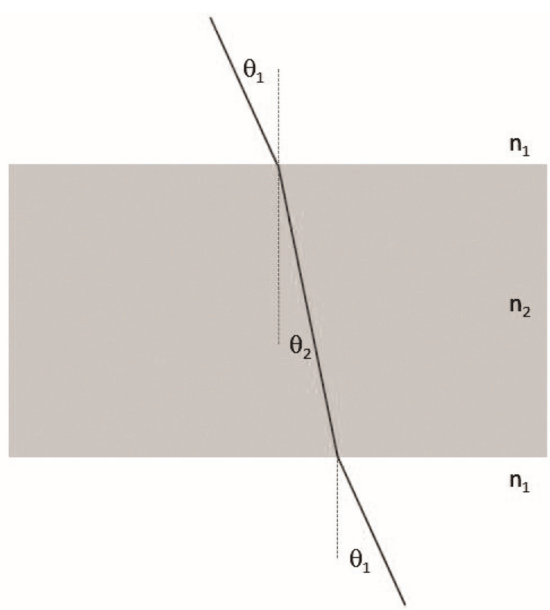


Figure 2-17 *A graphical representation of Snell's Law of refraction, showing the angle of incidence, θ_1, the angle of refraction, θ_2, the refractive index of the incident material, n_1, and the refractive index of the refracting material, n_2*

In this equation, n_1 is the refractive index of the material that the light starts in, and n_2 is the refractive index of the material that the light enters. The incidence angle, θ_1, is the angle that the light strikes the second material, as measured from the surface normal (a perpendicular line to the surface), as shown in Figure 2-17. The refracted angle, θ_2, is the angle at which the light travels within the second material, as measured from the surface normal. The angles that light travels in a material can be measured, so if the refractive index of one material is known (such as if $n_1 = n_{air} = 1.000$), then the refractive index of the second material can be calculated.

A condition of Snell's law describes cases in which light will not transmit from one material to the next. The condition is called *total internal reflection* and occurs when light strikes the boundary between two materials at the critical angle, θ_c, given by Equation 2-5.

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{2-5}$$

Technicians use a microscope-like instrument called a *refractometer* to make accurate refractive index measurements, usually in 589 nm light. This device works by placing a sample of the glass, plastic, polymer, or even liquid to be measured next to a reference material of a calibrated refractive index.

Figures 2-18 illustrates the operation of a refractometer. In the top drawing, $\theta_1 < \theta_c$, and light is transmitted through the sample. In the middle drawing, $\theta_1 > \theta_c$, which is the condition for total internal reflection. No light is transmitted through the sample. The refractometer identifies where no light is transmitted through the sample and uses Equation 2-5 to generate a calibrated scale (bottom drawing) for determining the sample's refractive index.

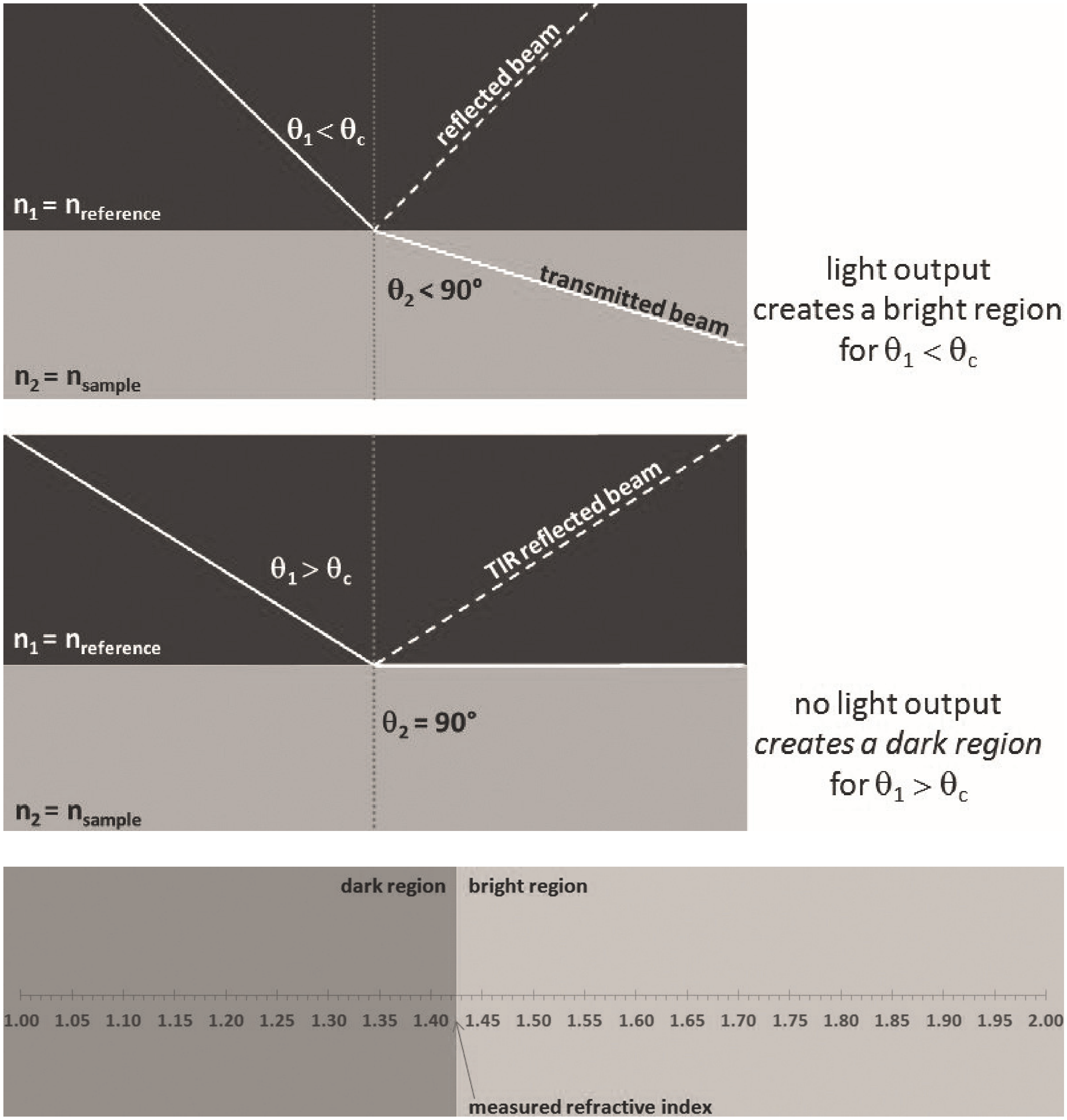


Figure 2-18 *The operation of a refractometer*

Figure 2-19 *A precision optics technician operates a refractometer to precisely measure the refractive index of a glass sample*

Polarimetry and ellipsometry are additional ways of measuring birefringence. *Polarimetry* measures the birefringence of an optical material, and *ellipsometry* measures the birefringence of an optical coating. These powerful measurement techniques are used to reveal the spectral, complex refractive index of optical materials. These techniques measure the amount of light in each linear polarization state (i.e., s- and p-polarized light), yielding the material's ordinary and extraordinary refractive indexes (n_e and n_o)—the difference between which equals the material's birefringence.

Figure 2-20 illustrates the techniques of polarity and ellipsometry. A linear polarizer creates equal amounts of s- and p-polarized light. This polarized light is directed to the surface of the witness sample at an angle of incidence equal to 45°. After reflecting from the witness sample surface, the amount of light then present in each polarization state is analyzed using another polarizer called an *analyzer*. The analyzer's results can be used to find the refractive index of each polarization state and also the birefringence of the material in the witness sample.

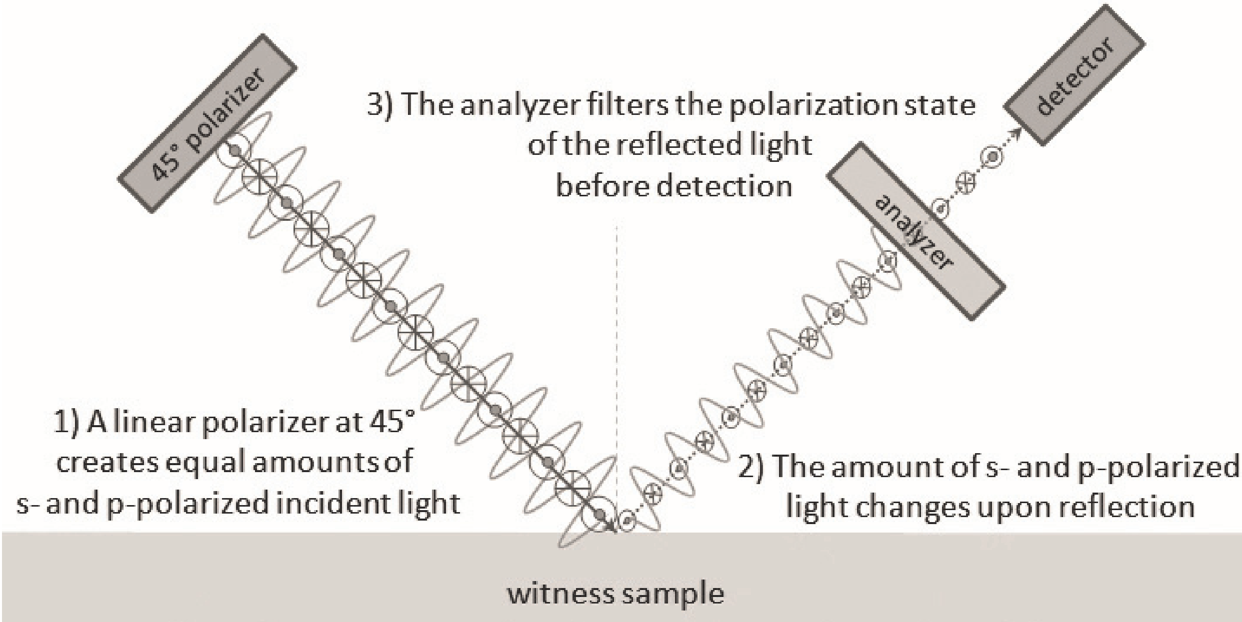


Figure 2-20 *Birefringence measurements using polarimetry and ellipsometry*

A variable-angle spectroscopic ellipsometer is shown in Figure 2-21. Its source is broadband and spectrally filtered, so the refractive index of a material as a function of wavelength may be measured at any reasonable angle of incidence.

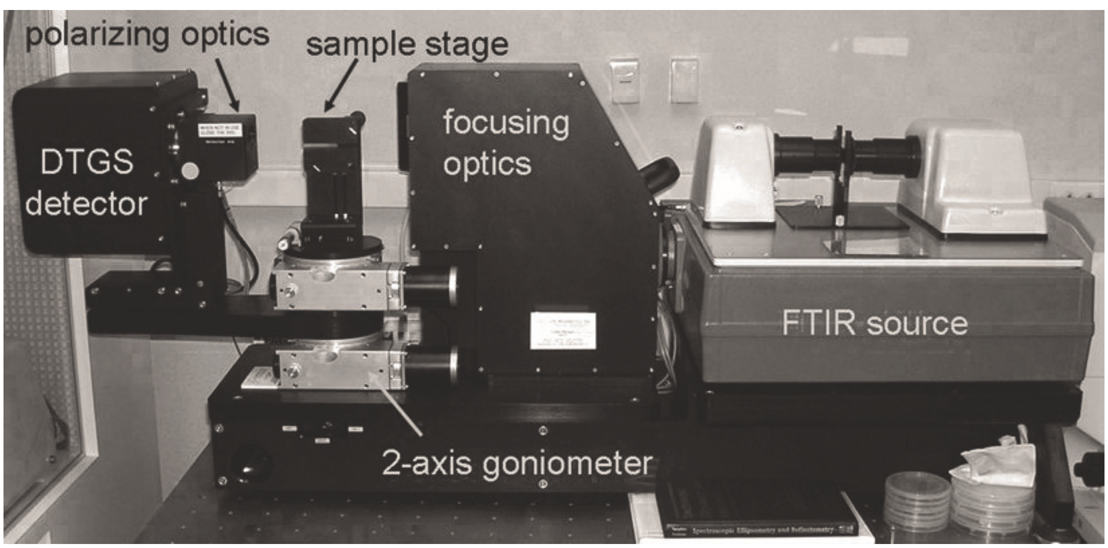


Figure 2-21 *A variable-angle spectroscopic ellipsometer by J.A. Woollam Company*

Radiometric Energy Transfer when Light Interacts with a Material

Light is a form of electromagnetic energy, so whenever light interacts with a material surface, energy is transferred. The energy is either transmitted through the surface, specularly reflected or diffusely scattered by the surface, or absorbed into the material. To measure and quantify the portion of energy that undergoes these processes, the total energy incident must be known. The incident energy is split due to these processes:

$$\mathrm{I}(\lambda) = \mathrm{T}(\lambda) + \mathrm{R}(\lambda) + \mathrm{A}(\lambda) \qquad (2\text{-}6)$$

The quantity $\mathrm{T}(\lambda)$ represents the portion of incident energy transmitted through the surface, $\mathrm{R}(\lambda)$ is the amount reflected by the surface, and $\mathrm{A}(\lambda)$ is the amount absorbed into the material. Often, scattering is negligible for precision optics, so that $\mathrm{R}(\lambda)$ represents only specular reflection, but some applications require detailed scattering measurements that will be covered in the next section. The following three simple ratios represent the mathematical quantities called spectral transmissivity, spectral reflectivity, and spectral absorptivity of a material.

$$\mathrm{t}(\lambda) = \frac{\mathrm{T}(\lambda)}{\mathrm{I}(\lambda)} \qquad \text{spectral transmissivity} \qquad (2\text{-}7)$$

$$\mathrm{r}(\lambda) = \frac{\mathrm{R}(\lambda)}{\mathrm{I}(\lambda)} \qquad \text{spectral reflectivity} \qquad (2\text{-}8)$$

$$\alpha(\lambda) = \frac{\mathrm{A}(\lambda)}{\mathrm{I}(\lambda)} \qquad \text{spectral absorptivity} \qquad (2\text{-}9)$$

These qualities are always **spectral quantities** that depend on the wavelength of the light. Therefore, combining Equations 2-7 through 2-9 with Equation 2-6 shows that the full 100% of the incident light, $\mathrm{I}(\lambda)$, is either transmitted, reflected, or absorbed:

$$100\% = \mathrm{t}(\lambda) + \mathrm{r}(\lambda) + \alpha(\lambda) \qquad (2\text{-}10)$$

Transmissivity and reflectivity are relatively straightforward parameters to measure if the incident light can be measured. Typically, an optical power meter is used to measure the incident light, and the same power meter can be used to capture the light that transmits through or reflects off the surface being measured. However, it is much more difficult to accurately measure the amount of light that is absorbed, particularly if the absorptivity is a very small quantity. Absorptivity can be calculated using Equation 2-10 if the transmissivity and reflectivity are accurately measured, but this is not an adequate or accurate method for low-absorption materials.

A good way to assess a material's absorption, also known as *attenuation*, makes use of the Beer-Lambert Law. The amount of radiation that transmits through a material decreases exponentially due to absorption as light propagates through its thickness:

$$\frac{T(\lambda,z)}{I(\lambda)} = e^{-a(\lambda)z} \tag{2-11}$$

This is an expression for the **spatial** transmission, in which $a(\lambda)$—not to be confused with $\alpha(\lambda)$—is the *spectral attenuation coefficient* with units of inverse distance. That is, as light propagates into a material, it is attenuated exponentially as a function of distance into the material, z, as shown in Figure 2-22.

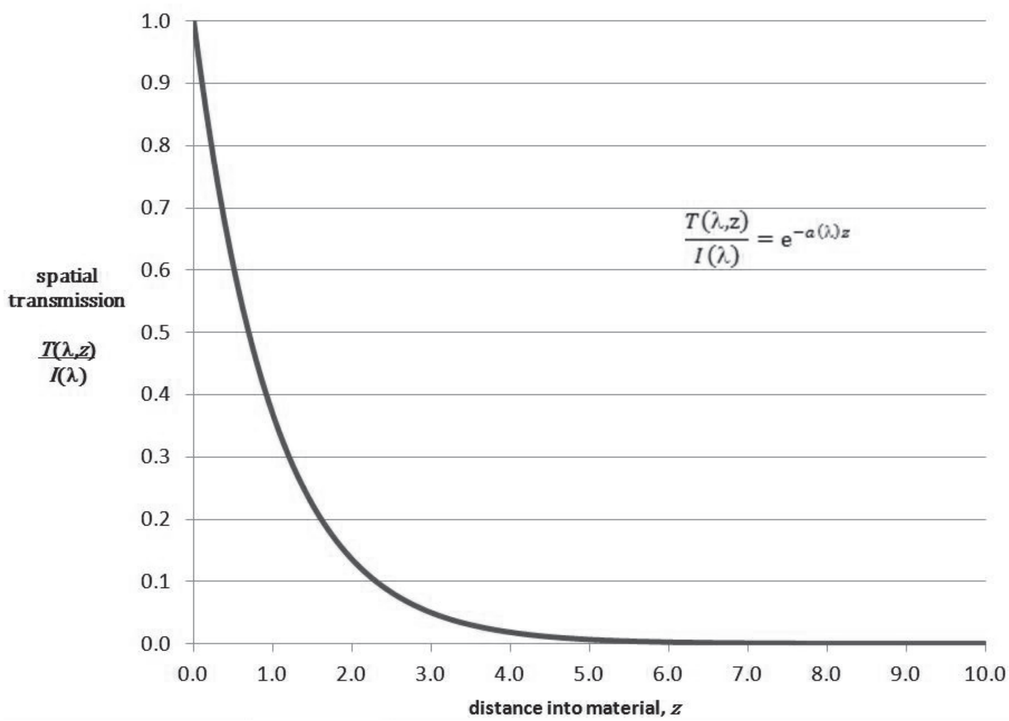


Figure 2-22 *Spatial transmission into a material due to Beer-Lambert attenuation*

Just as materials can transmit, reflect, or absorb energy, they can also emit optical energy. Emission of light by precision optics is not common in the fabrication, quality assurance, or metrology of precision optics, but it is important to understand the emissive effects of optical materials.

To relate emission to absorption, consider Kirchhoff's Law, which states that at each wavelength, absorptivity equals emissivity.

$$\alpha(\lambda) = \varepsilon(\lambda) \tag{2-12}$$

Strongly absorbing materials such as amorphous carbon (graphite, soot, lamp black), black paints, and completely dark cavities all emit radiation well and may be called *optical blacks*, while shiny, polished metals have low absorptivity and emissivity. This is why coils on an electric stove are matte black metal, rather than shiny silver metal. The grates of high-quality grills are coated with a good emitting material. As these dark surfaces are energized (heated), they glow (emit) a broad band of light in the infrared and visible portions of the spectrum. It takes considerably more input energy (e.g., electricity) to cause shiny silver materials to emit the same amount of energy, because their emissivity can be 10 to 10,000 times lower than a matte black material.

Excellent emitters/absorbers can emit/absorb many wavelengths of light over a large range, known as broadband light. These materials emit or absorb light according to the *blackbody equation,* a mathematical representation of an ideal, perfect emitter with unit emissivity ($\varepsilon(\lambda) = 1$). In practice, though, any material with $\varepsilon(\lambda) > 0.99$ is referred to as a blackbody. If $\varepsilon(\lambda)$ is lower than 0.99, then the material is known as a *graybody*.

Absorptivity and emissivity are both relevant to precision optics used in infrared or high-energy/high-irradiance applications. If a material absorbs energy well, it will also emit energy well. In many infrared systems, this may mean that the absorbing areas of an optical element may be emitting light at the infrared wavelengths that the system is trying to image! This creates stray light and other image-quality-reducing effects in an infrared system. If a precision optic has an absorptive region and this optic is used in a high-energy/high-irradiance system, too much energy may be absorbed, causing cracks or *fractures* in the optic. Unless they are part of the design, absorptive/emissive materials must be removed from precision optics and their coatings to avoid these harmful effects.

Not all materials emit broadband light. In fact, some materials are naturally excellent emitters of narrowband light. *Luminescence* is an important optical property of a material that relates its narrowband optical emission to its atomic structure. If luminescent materials are excited (for instance, electrically, chemically, or even mechanically), they will emit only particular colors. A familiar effect is electroluminescence, the principle on which light-emitting diodes (LEDs) operate.

A form of luminescence occurs when a material absorbs and re-emits light due to a phenomenon known as *fluorescence*. Fluorescence is the optical energy that is released by a material after absorbing short wavelength light and re-emitting it as a longer wavelength light. For example, if high energy, short wavelength ultraviolet light is incident on a fluorescent material, it may be re-emitted as longer wavelength, lower energy light in the yellow, orange, or red spectral regions. Good examples of this phenomenon are glow-in-the-dark phosphors, shown in Figure 2-23.

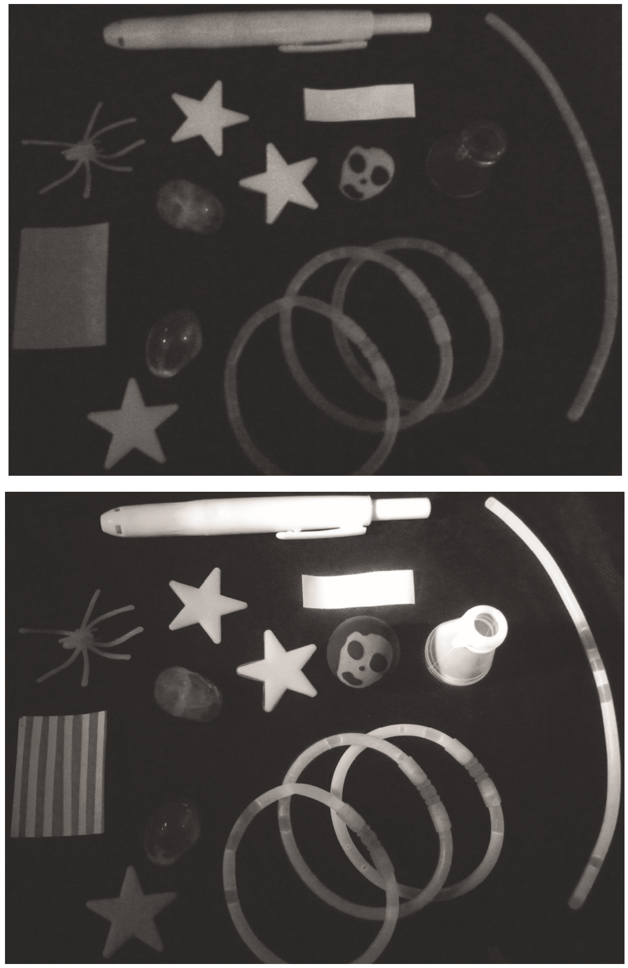


Figure 2-23 *The objects shown fluoresce reds, oranges, yellows, and greens when illuminated in violet light. (The two objects between the stars are fluorescent crystals.)*

Fluorescence is an important property of many optical systems (for example, laser systems and conventional office and industrial lighting), but it can be detrimental to the performance of a precision optical system. Imaging systems do not function well when one of their lenses is glowing at the same color it is designed to image. Drawings of precision optics may specify a threshold for allowable luminescence (fluorescence) of an optical material, since some glasses naturally emit light.

Measurement of Radiometric Energy Transfer

Many different types of systems are available to measure a precision optical element's reflection, transmission, absorption, emission, and scatter. These radiometric quantities are spectral (depend on wavelength), and dependent on the angle of incidence of the light. It is usually the optical coatings, not the substrates themselves, that make the precision optics' radiometric performance sensitive to the angle of incidence. When performing quality assurance inspections, only these angles of incidence used in an application of the optic need to be measured.

Measurement of Reflectivity and Transmissivity

Reflectivity and transmissivity are reasonably straightforward quantities to measure. The challenge comes in making a system that will measure these properties at many different wavelengths and angles of incidence. Instruments often used to measure reflectivity and transmissivity are called *spectrophotometers* (for ultraviolet/visible radiation) or *spectroradiometers* (for infrared radiation). These instruments are designed to make absolute measurements of reflectivity and transmissivity. When using these instruments, the witness sample is placed in a collimated beam that is emitted from a monochromator at the desired incidence angles using a rotation stage called a goniometer. Then the monochromator varies the wavelength of the light across a specified spectrum. The light interacting with the sample is measured by a detector. This produces a data plot of transmitted or reflected energy as a function of wavelength for each angle of incidence. Witness sample measurements are compared to reference measurements to determine the reflectance or transmittance of the sample.

Reflectivity and transmissivity are typically measured in one of two configurations. Dual-beam measurements simultaneously measure a reference material in one beam path and the sample in a second beam path. Figure 2-24 shows a typical transmission-measurement configuration for a dual-beam instrument. Single-beam instruments (Figure 2-25) require separate measurements to be performed for the reference and sample materials. Reflectivity measurement requires the source to be diverted through a series of mirrors, as shown in the figure. This allows measurement for various angles of incidence on the witness sample. Figure 2-26 shows a spectroradiometer in a characterization laboratory.

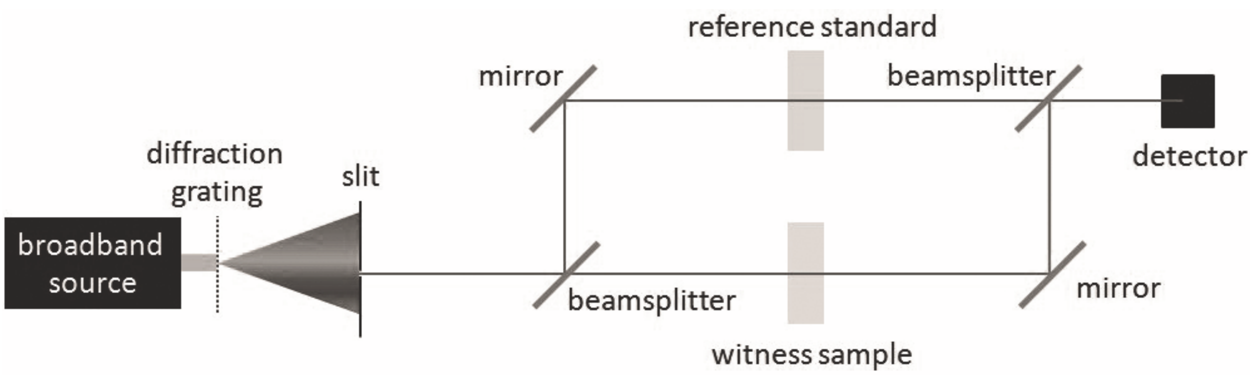


Figure 2-24 *A dual-beam transmissivity-measurement configuration for a spectrophotometer or spectroradiometer, used to measure the transmissivity of a witness sample relative to a calibrated reference standard. In the case shown, the grating is allowing green light to be tested. Other wavelengths may pass through the slit by moving the grating.*

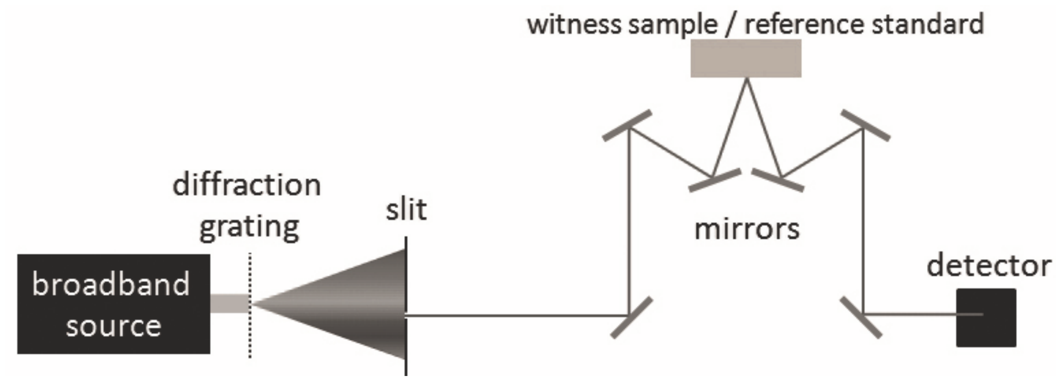


Figure 2-25 *A single-beam reflectivity-measurement configuration for a spectrophotometer or spectroradiometer, used to measure the reflectivity of a witness sample or reference standard at various angles of incidence (achieved by adjusting the mirrors). This single-beam setup requires that the reference standard and the witness sample are interchanged, and their data can be later compared using the instrument's software.*

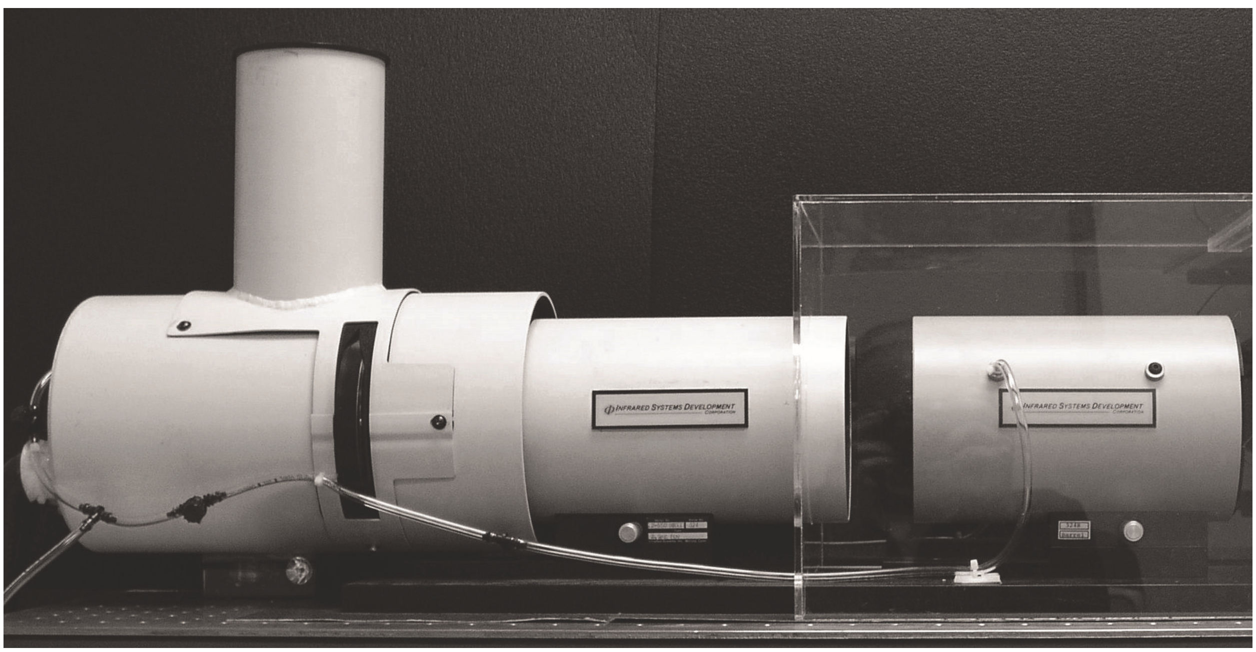


Figure 2-26 *This spectroradiometer measures optical properties in the infrared from 1 to 15 micrometers*

The reference material used in these single- and double-beam measurements is typically a volume of air or vacuum, or another calibrated material with a known reflectivity or transmissivity. If the optical sample being measured happens to be a liquid, the reference material should be an empty container that is identical to the container holding the sample being measured. This way, when the sample is compared to the reference, the light transmitted and reflected by the container will cancel out and not affect the measurement.

In summary, the operational procedure for spectrophotometers and spectroradiometers is as follows:

- A broadband source is directed into the instrument.
- The light is split into its spectrum by a diffraction grating or dispersing prism. This monochromator sends each wavelength sequentially toward the witness sample.
- Each wavelength then transmits through or reflects from the witness sample.
- A detector measures the transmitted or reflected light at each wavelength, building a plot of transmitted or reflected energy as a function of wavelength.
- This procedure is either simultaneously or sequentially conducted using a reference material.
- The ratio of the light transmitted through or reflected from the witness sample to the light transmitted through or reflected from the reference material gives the transmittance or reflectance, respectively, of the witness sample as a function of wavelength.

The instrument's software usually performs these calculations and reports the measured results as a plot of the sample's transmittance or reflectance as a function of wavelength. Measured radiometric data should always be reported graphically and in an electronic, tabulated format. The range of wavelengths measured should cover the wavelengths to be used in the various applications of the precision optical element, plus a few tens of nanometers on either end.

In another common radiometric measurement system, all transmitted or reflected colors are measured simultaneously. This system uses a Michelson interferometer to acquire data, and measurements are automatically processed using a mathematical method called Fourier analysis. This technique is most often used in industrial labs that measure components for infrared systems via an instrument called a *Fourier-transform infrared (FTIR) spectrometer*. Though more complicated to operate, the FTIR has significant advantages over spectroradiometers in that all light is collected at once, allowing rapid spectral measurements that do not require a wide range of light levels to be detected. Figure 2-27 shows an FTIR system.

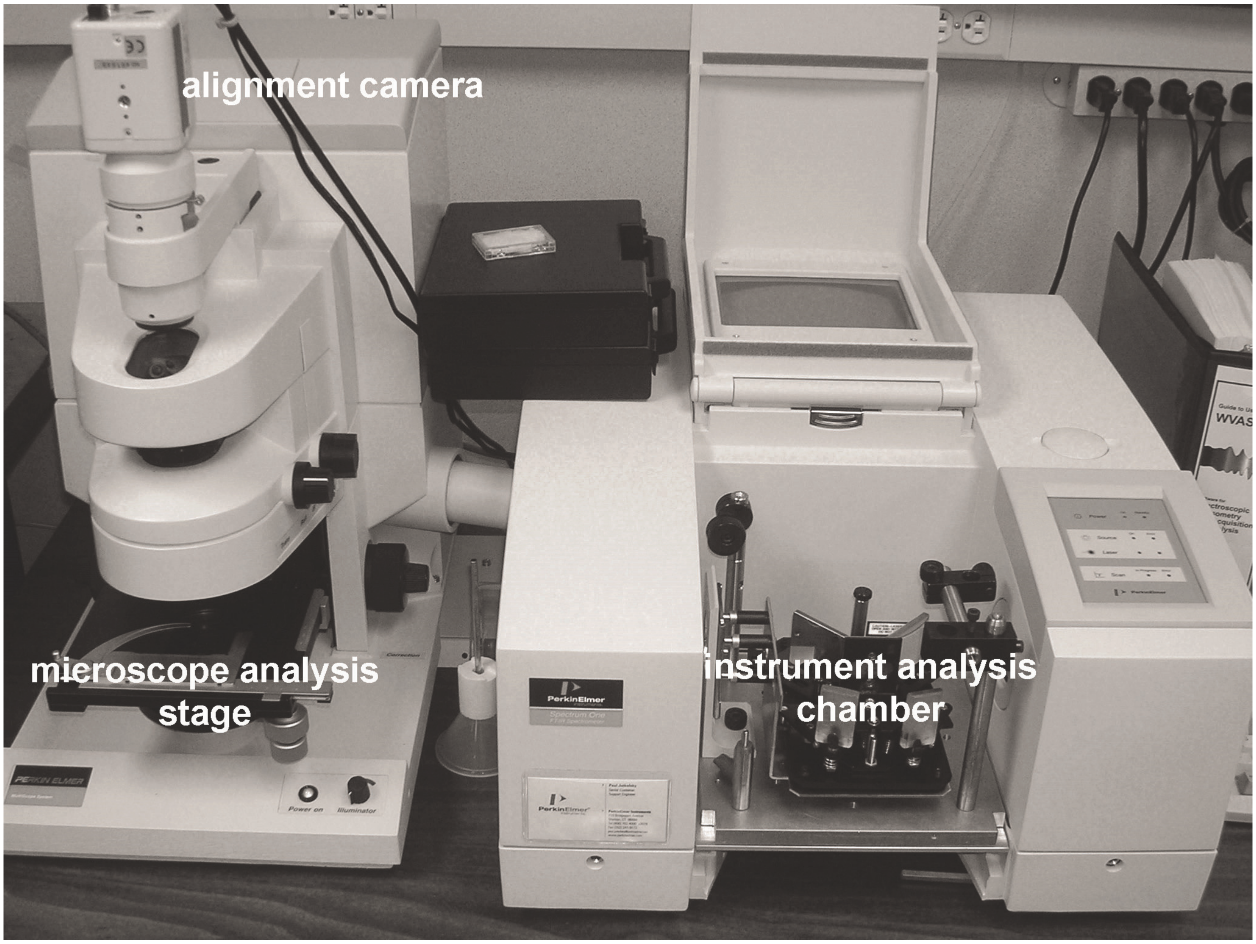


Figure 2-27 *This FTIR spectrometer is capable of measuring the spectral properties of materials from wavelengths ranging from 2 to 25 micrometers. A microscope accessory (on the left) is able to measure extremely small samples.*

Measurement of Absorptivity, Emissivity, and Scattering

In many applications, absorptivity and scattering are assumed to be negligible or are assumed to account for the light remaining at each wavelength after the transmissivity and reflectivity have been measured and tabulated. For instance, if 95% of the light at 550 nm is reflected and 4% is transmitted, it is assumed that 1% of 550-nm light is either absorbed or scattered, to account for 100% of the input radiation. This degree of understanding is typically adequate for most applications. Keep in mind that this calculation needs to be performed on a wavelength-by-wavelength basis.

Advanced precision optics may require more thorough characterization of the optic's absorptivity or scattering. In particular, optics used with high-energy light require detailed absorptivity measurements because if the optic absorbs too much light, its optical performance can change or its mechanical performance can fail due to thermal strain or coating damage. Optics used in high-resolution imaging systems require careful scattering measurements. Imaging problems, including stray light, blooming, and mid-spatial frequency error, will result from highly scattering optics.

Absorption is best characterized by a technique called *calorimetry*, a precision temperature measurement. Measurements of precision optics often employ laser calorimeters that carefully compare the temperature of a laser-irradiated sample to the temperature of an unirradiated sample. Slight temperature changes correspond to the radiation absorbed. The temperature-measuring element (the "thermometer") may be fabricated in contact with or even directly onto the witness sample by applying small metal layers that create temperature-dependent resistors called *bolometers*. From calibrated bolometers, a voltage change can be measured that corresponds to the amount of radiation absorbed. Using this technique, extremely low absorptivity values below 10^{-6} (1 part per million) can be measured. Calorimetry measurements are often made in a vacuum to reduce ambient, convective temperature variations. Depending on how the test is conducted, measured absorption may be presented as unitless spectral absorptivity, $\alpha(\lambda)$, or as a bulk spectral absorption coefficient, $a(\lambda)$, via the Beer-Lambert Law, in units of inverse distance.

Scattering may be characterized by similar techniques used for reflectivity, since it is a form of reflectivity—scattered light is diffusely reflected light, whereas reflectivity quantifies specularly reflected light. Like reflectivity, scattering may be generally characterized as a ratio of the total scattered light to the total incident light. This ratio is commonly referred to as the material's *albedo*, and it may be expressed as a ratio or percentage. For example, the albedo of the earth as viewed from space is generally accepted to be about 30%, depending on cloud cover and terrain. The albedo of snow can range above 90%, and that of soil is around 15% to 20%.

More detailed measurements characterize scatter as a function of angle. These measurements are based on optical functions called the *bidirectional reflectance distribution function (BRDF)* or the *bidirectional transmittance distribution function (BTDF)*. The BRDF represents the amount of light that is scattered to all angles back toward the source, and the BTDF represents all of the light scattered to all angles through the sample, away from the source. These functions are complicated, but they provide information on the reflected and transmitted light through an optic for an angle of incidence used in some application involving this optic. These functions are typically represented as a plot of scattered energy (or power) versus angle. In a BRDF measurement, the sample is left in one place, with the various colors of light incident at specific application angles. These measurements require high-resolution angular-positioning stages called *goniometers* that move the source(s) and detector(s) through all the angles the light might scatter.

To measure spectral emission or luminescence (fluorescence, electroluminescence, etc.), an optical source is measured by a single-element detector after its light passes through a monochromator or a series of spectral filters that separate the source into its constituent wavelengths. To make calibrated radiometric measurements of emission, a device known as an *integrating sphere* may be used to uniformly distribute the light over the surface of the detector, without any glints or nulls. LEDs are measured this way, per Standard CIE 127: 2007, which also allows for evaluation of other important radiometric source properties, such as the spatial distribution of the LED light.

LABORATORIES

Laboratory 2-A
Refraction Metrology

Theory

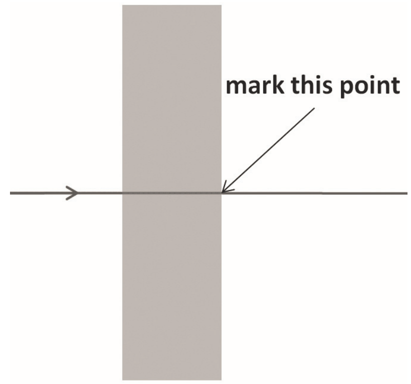
A refractometer is any device used to measure refractive index. Complex tools based on total-internal reflection are used in industry. However, a simple refractometer can be constructed using a light source, a ruler, and a protractor to measure the angles of incidence and refraction as light passes through blocks of polished glass or plastic. Snell's law can then be applied to calculate the refractive indexes of the materials measured.

Equipment

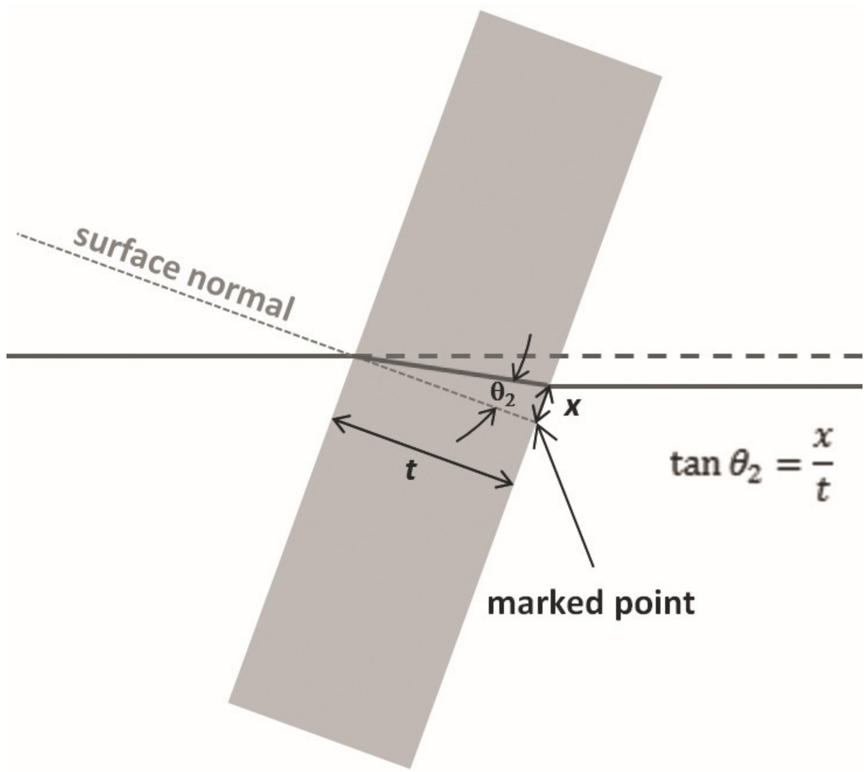
- Light source (1 per group, preferably a low-power laser or the PASCO light source with a narrow slit over its aperture)
- Polished, uncoated optical windows made of glass or plastic, without or with only a small amount of wedge; rectangular-aperture windows work well (2 to 4 per group)
- Ruler (1 per group)
- Protractor (1 per group)
- Micrometer or caliper (1 per group)

Procedure

1. Measure the thickness, t, of the window with a micrometer, calipers, or a ruler.
2. Direct a beam of light down the length of an optical bench and trace the beam along the length of the bench on a piece of paper.
3. Position the window in the path of the light and orient the window so that the light is returned to its source using the front-surface reflection (it may be dim). This sets the incidence angle, θ_I, equal to zero degrees (so-called "normal incidence").
4. In this orientation, use a felt-tip pen to mark a tiny dot at the point from which light exits the back surface of the window (as shown in the figure).



5. Locate the center of a protractor at the point at which the light hits the window.
6. Rotate the window **about this incidence point** by $\theta_1 = 20°$ from normal incidence, as measured by the protractor (rotate the protractor with the window). This causes the light to refract as it passes through the window.
7. With a ruler, measure the distance, x, from the marked point to where the beam now exits the output face of the window. From this distance, x, and the thickness, t, calculate the angle of refraction, θ_2, using the trigonometric equation in the figure.



8. Use Snell's law to calculate refractive index of the window material, n_2, knowing the refractive index of the incident material ($n_{air} = 1.000$), the measured angle of incidence, θ_1, (step 6), and the calculated angle of refraction, θ_2 (step 7).
9. Repeat steps 1 through 8 above for incidence angles of $\theta_1 = \pm20°, \pm30°, \pm40°$, and $\pm50°$ (and higher, if possible). This provides multiple measurements of θ_2 to average and determine a better statistical value for the refractive index, n_2.

10. Repeat steps 1 through 9 above to determine the refractive index of each window available.
11. Speculate about sources of error in your experiment. What effect would wedge have on these measurements?

Laboratory 2-B
Optical Shop Tool Fundamentals

Theory

Many different mechanical tools are used to perform dimensional measurements of optical and nonoptical components. The purpose of this lab is to gain experience using calipers, micrometers, height and depth gauges, gauge blocks, and other tools that are used in optical shops. This lab will also explore the concept of tolerance as it relates to reporting the dimensions of fabricated components. You will measure simple materials, including paper and metal parts, in addition to optical components. Compare your measurements to vendor measurements.

Equipment

- Length-measurement tools: ruler, calipers, micrometers (1 each per group)
- Height gauge and granite slab or optical bench (1 per group)
- Set of calibrated, precision-angle and -thickness gauge blocks (1 per class to share)
- Optical hardware to be measured, such as lenses, mirrors, windows, or prisms, along with vendor-provided metrology for these optics (10 total features per group, i.e., thickness, diameter, clear aperture, etc.)
- Other materials to be measured, including various thicknesses of paper, plastic, or metal components, such as screws, dowels, bar stock, rod stock, or any other parts that are fabricated to specific dimensions, along with vendor-provided metrology for these parts (10 total features per group, i.e., length, width, diameter, etc.)
- Low-power helium-neon or diode laser (1 per group)
- Transmissive optical window with wedge. Ensure the coating (or lack thereof) allows reflection of the laser wavelength from both surfaces. (1 per group)

Procedure

1. Assess and document the range, accuracy, and resolution of each length-measurement tool (ruler, caliper, micrometer, height gauge, etc.).
2. Verify that each of the length-measurement tools are well calibrated by measuring various calibrated thickness gauge blocks with each tool. Perform at least three measurement trials with each tool. Document how close the readings of the tools agree with the calibrated gauge blocks.

3. Use the length-measurement tools to measure the length dimensions of the available parts (optical and otherwise).

    a. Record each measurement in your lab notebook, making at least three measurement trials with each tool.

    b. Compare your measurements to the vendor's measurement by making a table with a column for each part measured, with a row for each measurement technique and trial number, and a second row for the vendor's measurement value.

    c. Estimate the nominal values and fabrication tolerances for each of the various features measured.

    d. Which dimensional features are best measured by which length-measurement tools? Specify at least one tool option for each common feature of a precision optical part.

4. Use gauge blocks to calibrate a laser-based wedge-measuring setup:

    a. Direct a laser beam onto a **thickness** gauge block and direct the laser beam directly back on itself into the laser cavity. (Fringes may begin to appear when the back reflection is well aligned. This can damage the laser if this condition is maintained for a long duration.)

    b. Place an **angle** gauge block directly atop the thickness gauge block. Measure how far away from the laser aperture the beam is reflected.

    c. Repeat with gauge blocks of various angles to create a calibrated target board in the plane of the laser aperture. Label each reflected beam position with the angle of the angle gauge block used to achieve that reflection.

5. Use the laser-based wedge-measuring setup to measure a wedged window:

    a. Direct a laser beam onto the wedged window. Each surface will reflect the beam back toward the laser, so the longer the distance the light propagates, the more accurately the separation of the two laser beam reflections can be discerned.

    b. Calculate the window's wedge angle by comparing the beam-to-beam displacement to the calibration performed in step 4.

    c. Calculate the window's wedge angle by dividing the beam-to-beam displacement by the distance between the window and the measurement plane (the plane of the laser aperture).

    d. What errors are associated with each technique? If one measurement technique is superior, explain why.

Laboratory 2-C
Focal Length Determination by Telescope

Theory

It is not difficult to assess the focal length of a positive lens by imaging distant light sources at optical infinity: the distance from the lens to the image is nominally the lens's focal length. This might be an inaccurate measurement, but it is an efficient estimation. It is much more difficult to quickly assess the focal length of a negative lens.

By constructing a simple, two-lens Galilean telescope by adding a negative lens to the appropriate positive lens to form a clear image of a distant object through the two lenses, allows you to quickly assess a negative focal length. In this configuration, the difference between the known positive focal length and the separation of the two lenses equals the focal length of the negative lens.

A Galilean telescope is operated in an *afocal* mode—its input and output are both collimated. That is, the input light comes from optical infinity, and it projects the image to negative infinity so that the user's eye can view the image while relaxed, without straining. Therefore, it is most accurate to measure the alignment of an afocal telescope with a collimated laser source and a simple interferometer called a *shear plate interferometer*. A shear plate creates straight-line fringes when collimated light passes through it, and curved fringes when the light is divergent or convergent (i.e., not quite collimated). You will use the shear plate first to measure the laser collimation, and then to measure the collimation of the two-lens Galilean telescope. Collimated output from the Galilean telescope requires proper spacing (afocal alignment) of the lenses so that the focal length of the negative lens can be accurately determined by subtracting the lens spacing from the positive focal length.

Equipment

- Positive lenses with focal lengths of approximately 50, 75, and 250 mm, all ≥25 mm in diameter (1 each per group)
- Negative lenses with focal lengths of approximately –12.5, –25, and –75 mm, all ≥12.5 mm in diameter (1 each per group)
- Optical rail or an optical bench with lens mounts (1 per group)
- Ruler (1 per group)
- Low-power helium-neon or diode laser (1 per group)
- 20x microscope objective and mount to diverge the laser (1 per group)
- A lens with a focal length of about +50 mm and a diameter of 50 mm, used to collimate the laser (1 per group)
- Shear plate interferometer (1 or 2 per class to share)

Procedure

1. Efficiently assess and document the focal lengths of each positive lens by imaging a distant source to a point and measuring the distance between the lens and the focal spot.
2. Mount the shortest focal length positive and negative lens pair on an optical bench or rail. Look through the negative lens and adjust the lens separation to obtain a clear, magnified image of a distant object. This may be subjective, since it is difficult to determine the lens position of best collimated focus. Measure the lens spacing, and using the focal length of the positive lens, calculate the focal length of the negative lens.
3. Repeat step 2 for the moderate focal length lenses.
4. Repeat step 2 for the longest focal length lenses.
5. Use the following procedure to set up and collimate a laser:
    a. Direct the laser into the back end (the end with the screw threads) of the 20x microscope objective.
    b. Locate the +50 mm focal length lens about 50 mm from the objective to capture and collimate the expanding beam.
    c. Measure the output of the +50 mm lens by locating a shear plate in the nearly collimated beam after the lens.
    d. Adjust the ~50 mm separation between the lens and the microscope objective until straight-line fringes appear on the shear plate display. The laser output is now a collimated, 50 mm diameter beam.
6. Align each of the three lens sets tested in steps 2 through 4 to this collimated laser beam, inputting the laser into the positive lens side of the afocal telescope.
7. Locate the shear plate in the output of the afocal telescope and assess the collimation. For each of the three lens sets, change the spacing to obtain the best collimation.
8. Measure the new lens separation of the telescope and again calculate the negative focal length for each negative lens.
9. Compare the results obtained by eye to the results obtained using laser interferometry. Document why the laser-based technique is more accurate.
10. Explore other positive-negative lens combinations. What optical parameters change when other lens pairs are used? Why are some pairs easier to align than others? Would it be possible to make a telescope using any of the available lens pairs?

PROBLEM EXERCISES AND QUESTIONS

1. Five lenses are made with the following clear aperture (CA) values:

   Serial number (S/N) 1: 25.469 mm, S/N2: 25.421 mm, S/N3: 26.101 mm, S/N4: 24.001 mm, S/N5: 24.999 mm.

   Which meet the drawing specification of 25.000 ± 1.000 mm?

2. The resolution of a micrometer is 0.010 mm. Why can or cannot it be used to meet a specification that requires a tolerance of ±0.010 mm?

3. What optical shop tools may be used to measure the length of a dimension on an optical part? Indicate which are the most accurate techniques.

4. Explain a technique that might be used to measure the 90° angle of a right prism.

5. You are asked to measure the thickness of an optical window to a resolution of ±1 mm. Which tool(s) might you choose?

6. You are asked to measure the thickness of an optical window to a resolution of ±0.01 mm. Which tool(s) might you choose?

7. When a flat window is being tested against a flat test plate, only circular Newton's fringes

8. When a flat window is being tested against a flat test plate, only linear Newton's fringes form. Is there a problem with the window? Explain what is happening.

9. Use the Schott glass map to state whether the following glasses are crown or flint glasses:
   a. refractive index 1.572, Abbe number 55.9
   b. refractive index 1.75, Abbe number 49.5
   c. refractive index 1.75, Abbe number 50.5
   d. glass code 744448
   e. glass code 620603
   f. glass code 700298

10. In an assessment of a glass surface to be used in a touch-screen display, the total transmitted energy of visible light is measured to be 95.95%, and the total reflected energy is measured to be 3.97%. What percentage of the energy was absorbed or otherwise lost in the glass?

11. Explain why calorimetry is required to measure low levels of absorption.

12. A simple singlet lens is measured to transmit 90% of the 589 nm light incident on it. Its first surface reflects 4% of the incident 589 nm light. Explain what could have happened to the remaining 6% of the incident 589 nm light.

13. Explain the difference between how you would measure light that directly reflects off a surface versus how you would measure light that diffusely reflects off a surface.

14. When light reflects from a surface, it will be polarized, particularly for high angles of incidence. Considering this, when light reflects from the hood of your car, causing glare into your eyes as you sit in the driver's seat, which polarization state is more likely to be reflected into your eyes, and which polarization state is more strongly transmitted into the hood?

15. Explain and sketch the difference between the BRDF and the BTDF.

Advanced Problem Exercises and Questions

16. It is interesting to observe Snell's Law in nature. Consider a glass of water with a straw in it. If the straw goes straight into the water (i.e., $\theta_1 = 0°$), refraction is not noticeable. However, if the straw is tilted at $\theta_1 = 30°$, it will appear bent. Light enters the water from air ($n_1 = 1.00$), and the refracted angle is 22.08°. Use this information to calculate the refractive index of water.

    Ethylene glycol (antifreeze) has a refractive index of $n_{\text{ethylene gylcol}} = 1.445$. Calculate the angle to which the straw would appear bent if your glass were full of ethylene glycol instead of water.

17. Derive the critical angle formula from Snell's law.

18. What is the critical angle for an optical fiber with a cladding index of 1.518 and a core index of 1.623?

19. What is the Abbe number of water?

    The refractive index of water is $n_d = 1.33250$, $n_F = 1.33556$, $n_C = 1.33100$.

20. Using a spectrophotometer, light is incident on a coated mirror to measure its spectral reflectivity. This particular source outputs light at the power levels indicated in the table below for each wavelength. The table also shows the measured power reflected from the material. From these data, calculate and plot (using spreadsheet software) the spectral reflectivity for this coated mirror. For what color(s) is this coating highly reflective?

wavelength [nm]	measured power incident [mW]	measured power reflected [mW]
400	0.23	0.004
425	0.14	0.04
450	0.25	0.04
475	0.33	0.11
500	0.41	0.03
525	0.55	0.02
550	0.69	0.08
575	0.64	0.13
600	0.71	0.55
625	0.63	0.61
650	0.88	0.25
675	0.65	0.08
700	0.54	0.18

21. Having wedge in an optical window will shift or deviate the beam's direction by a different angle for each wavelength due to the dispersion of the glass. This is how prisms work. If an optical window has 75 milliradians (~4.3°) of wedge and is made from a material that has a refractive index of 1.45 for red light and 1.47 for violet light, how will red light be separated from violet light on a wall 10 meters from the wedge?

22. When using a spherometer, the *sag* is the distance from its central tip to the plane formed by the outer three tips. The parameter *d* is the average distance between the outer three tips, per the following equation:

$$R = \frac{sag}{2} + \frac{d^2}{6 \cdot sag}$$

If *d* equals 30 mm for the spherometer in your shop, what is the radius of the optical surface if you measure a sag of 200 mm?

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Specifications and Drawings for Precision Optics

Module 3

of

Quality Assurance of Precision Optics

PRECISION OPTICS SERIES

National Center for Optics and Photonics Education

PREFACE TO MODULE 3

This is the third module in the *Quality Assurance of Precision Optics (QAPO)* course. This course provides an overview of processes used to manufacture precision optics elements; introduces quality assurance practices required to identify, inspect, and measure optical components; and presents a comprehensive review of measurement practices essential to ensuring the quality of optical components. This course is designed for students seeking a basic understanding of how precision optics components are produced and what techniques are used to validate their adherence to industry standards. This course was designed to comply with the 2nd Edition of the National Precision Optics Skill Standards for Technicians.

Module 3, Specifications and Drawings for Precision Optics, provides information on how specifications for optical components should be presented and measured. Proper drawings of precision optics are described per the International Organization for Standardization (ISO) 10110 Optical Drawing Standard. This module explains the thirteen sections of ISO 10110 that define physical features and properties of precision optics, and it describes techniques for measuring these parameters.

The material presented in this module involves technical terms and measurement techniques that are often unique to the field of precision optics. To make certain users have the vocabulary needed to understand the concepts presented, a glossary of technical terms and scientific concepts is included at the end of this course. We highly recommend that you review this glossary before moving forward in this module. Terms in the glossary will be italicized throughout the course material.

CONTENTS OF MODULE 3

Module 3
Specifications and Drawings for Precision Optics

INTRODUCTION

Clear communication is critical in all technical fields. To communicate how a precision optical element should be made, optics are specified by requirements written on a technical drawing, like a blueprint. These drawings show pictures of the optic from multiple perspectives, and the specifications are written with nominal values and tolerances. Traditionally in the United States, precision optics designers and manufacturers communicated technical specifications using an assortment of standards that were loosely based on U.S. military specifications. However, many U.S. manufacturers have begun to adhere to a single optical drawing standard: the International Organization for Standardization (ISO) 10110 Optical Drawings Standard, referred to as ISO 10110. This internationally accepted standard ensures clear, concise, and comprehensive communication among all optical designers, optical engineers, optomechanical engineers, and precision optics technicians as they design, fabricate, and characterize precision optics. This module covers the specifications that precision optics drawings typically require and the measurements required to characterize the specified parameters.

PREREQUISITES

OP-TEC *Fundamentals of Light and Lasers*: Modules 1-1, 1-2, 1-4, 1-5
OP-TEC *Quality Assurance of Precision Optics*: Modules 1 and 2

Students should be able to calculate ratios and angles, apply scientific notation, perform dimensional analyses of units, understand the use of geometric equations to describe conic sections (parabolas, ellipses, etc.), and use trigonometric formulas and algebraic equations.

OBJECTIVES

- Read and interpret technical drawings and specifications.
- Use design specifications, technical drawings, and/or government documentation to meet specifications and tolerances.
- Inspect and evaluate material certification sheets to match print specifications.
- Maintain prescribed documentation of bulk materials using a job jacket or its equivalent.
- Document process changes and non-conformances and identify preventative and corrective actions to improve process control.
- Participate in the development of inspection plans that use the appropriate metrology for all measured specifications.
- Document final inspection results according to instructions, procedures, and/or specifications to close job jacket or equivalent.
- Use quality assurance criteria to determine deficiencies in materials and optics using established design specifications.
- Use statistical process control guidelines for sampling finished components.
- Interpret design drawings for coating specifications.
- Store optics in appropriate container with environmental controls.
- Determine and select, using written instructions and specifications, appropriate packaging for protecting, storing and shipping optics.
- Evaluate shipping conditions for finished optics to determine appropriate packaging.
- Inspect finished optical components to ensure compliance with established specifications following accepted procedures.
- Test finished components by appropriate means including test plate or interferometric techniques to ensure compliance with design specifications.
- Describe fundamental mechanical properties of optical materials, including hardness, toughness, brittleness, ductility, scratch resistance, cleavage, fracturing, and chemical stability, and assess their relevance to specified manufacturing processes.
- Describe basic stress-strain relationships for optical materials, and the associated regions of plastic and elastic deformation, up to material fracture.
- Distinguish the flaw types particular to crystalline optics, including cleavage, crystal structure, and grain boundaries.
- Inspect surface quality of finished product to comply with appropriate scratch-dig standards as specified on the component drawing or specification sheet.
- Understand the use of the techniques required to assess internal and surface flaws of a precision optics, including loupes, optical profilers, and interferometers.

- Measure and analyze homogeneity of materials using interferometry techniques.
- Use a loupe to identify bulk material defects such as inclusions, bubbles, striae, and fractures.
- Describe fundamental properties of optical materials related to the environment, including coefficient of thermal expansion (CTE), thermal shock, abrasion, and corrosion.
- Determine optical, chemical, thermal, and mechanical properties of selected materials from handbooks, supplier specification sheets, and Internet sources, and assess their relevance to specified manufacturing processes.
- Understand the applications of environmental testing techniques, including thermal and abrasion tests.
- Use polarization measurement techniques to identify internal stress.
- Inspect finished optical components to ensure compliance with established specifications.
- Measure surface roughness using white light interferometry or other optical means.
- Measure surface quality using appropriate equipment (e.g., scratch-dig inspection box, microscope, loupe, and magnifiers).
- Measure surface error, reflected wavefront error (RWFE), or transmitted wavefront error (TWFE) using appropriate equipment (e.g., interferometers, test plates, profilers, or coordinate measuring devices), and determine deviations from specifications in dimensionality.
- Use proper cleanroom and air-flow workbench procedures.
- Monitor air flow filtration, room pressure, air velocities, temperature, and relative humidity of cleanrooms.
- Use established procedures for personnel gowning for cleanroom operations, including booties and beards.
- Understand optical cleanliness and contaminant descriptions, including environmental (cleanroom) cleanliness standards, surface cleanliness standards, and non-volatile residue (NVR).
- Apply accepted standards to maintain work area cleanliness, including use of proper procedures for entering and exiting air locks and door locks in a cleanroom facility.
- Interpret clean room Class Ratings required in optics fabrication (e.g., Class 100, 1000, and 10,000).
- Understand and use the solvents required to clean precision optical surfaces.
- Ensure physical safety in handling hazardous materials by marking material containers with appropriate material safety data sheet (MSDS) identifications.
- Identify health hazards associated with specific materials and processes and use accepted practices to ensure health of self, others, and the environment.

- Follow material handling procedures to ensure physical safety, avoid contamination, and maintain material inventory and identification.
- Prepare fixtures for mounting starting material as part of the fabrication process.
- Interpret assembly drawings.
- Clean, prepare, and inspect optical surfaces prior to assembly per requirements.
- Use proper alignment techniques for assembly processes.
- Use proper procedures in mixing, degassing, applying, and establishing cure times for adhesives and epoxies.
- Select and/or use appropriate or required optical adhesives or epoxies.
- Align and pot elements in cells.
- Mount optical components in mechanical assemblies using prescribed methods.
- Measure conformance and performance of optical assembly via mechanical and/or optical means.
- Determine root cause of any non-conforming assemblies.

SCENARIO

As a buyer for an aerospace company, Anita has to interact with customers, vendors, and her corporate technical staff. She doesn't need to understand every word on a design drawing for an optical component, but does need to know the right members on her technical team to contact when questions arise. To advance her career and her understanding of her company's technical products, she attended a short course that covered all the details that might be included on drawings of precision optics. She learned which aspects of drawings are related to the mechanical, optical, and electrical teams, and which aspects directly involve the technical inspection and quality assurance team. She is now able to communicate more clearly with the engineers and technicians in her organization and with the vendors that support her company. With this newly acquired skill, Anita has become a greater asset to all the production teams she serves.

BASIC CONCEPTS

Interpreting Drawings that Specify Precision Optical Components

Optics may be drawn and specified in any manner that the optical designer chooses, which can lead to confusion and many questions from the manufacturer. To solve this problem, many designers use a single optical drawing standard that is accepted internationally: the International Organization for Standardization's ISO 10110 Optical Drawings Standard, *Preparation of drawings for optical elements and systems*. In practice, this standard is referred to as ISO 10110, read as "eye-ess-o ten-one-ten" or, simply, "the thousand." This standard sets specific rules for making optical fabrication drawings and defines how the optical parameters should be specified. These rules are defined comprehensively in the ISO 10110 Standard itself and this module covers the most common and important rules. Later sections of this module will describe appropriate methods for qualitatively evaluating or quantitatively measuring each specified parameter.

A fundamental aspect of an optical drawing is the drawing of the optic itself. It provides a dimensioned sketch of what the fabricated part should look like. Standardized drawing practices known as geometric dimensioning and tolerancing (GDT) (per ISO Standard 5459) are used to draw all optics to a reasonable scale of the *nominal* values with associated tolerances. American Society of Mechanical Engineering (ASME) standard ASME Y14.5-2009 (or ASME Y14.5M-1994) is used as the mechanical drawing standard for ISO 10110 drawings. This standard provides coordinate systems, scaling, reference surfaces, and physical constraints for all mechanical features. The ISO 10110 Standard uses metric units, and all unspecified linear dimensions must be in millimeters. Tolerances follow the nominal specifications, as superscripts for the higher-limit tolerance, and as a subscript for the lower-limit tolerance. For example, in N_L^H, N is the nominal value, H is the higher-limit tolerance, and L is the lower-limit tolerance, so that $N + H$ is as large as the parameter may be, while $N - L$ is as small as the parameter may be.

Unless otherwise specified, the reference temperature for all optical drawings is 20°C. Standard ISO 7944 is often used to set the reference wavelength (the mercury e-line of 546.07 nm) for ISO 10110 drawings, but often, the wavelengths used for the part's application are written explicitly on the drawing. All ISO 10110 drawing must include the text "Indications in accordance with ISO 10110" or a variation, such as "Ind. acc. ISO 10110."

Most optics are drawn in cross-sectional view, but more complicated optics may be drawn from multiple perspectives, such as a plan view (from above, as in a "floor plan" view), a side view, or even an isometric view drawn from first-angle projection. The right side view is located to the left of the plan view, as shown in Figure 3-1, which also shows a third-angle view of the same object. Since the clear aperture of a complex optical element, such as a prism, is difficult to show in three dimensions, multiple views may include shaded or cross-hatched regions that indicate the optically significant region.

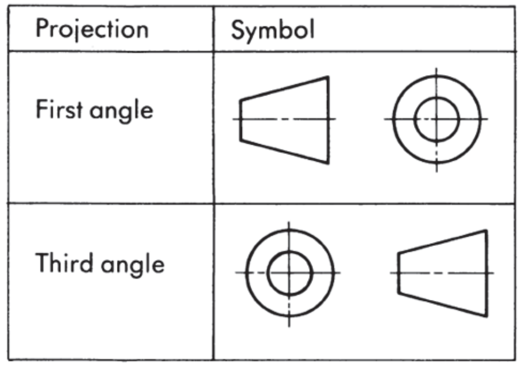
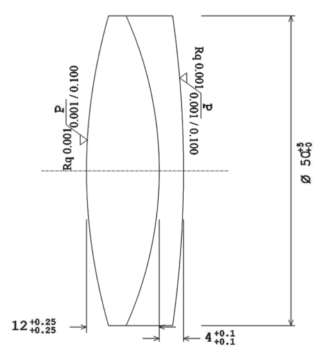


Figure 3-1 *Comparison of the first-angle projection view to the third-angle projection view of the same object*

In all views, if possible, optical elements are drawn with incident light entering from the left and with the optical axis horizontal. The optical axis is drawn as a dash-dot-dot line (— · · — · · —), and the optical center line (unless it coincides with the optical axis) is drawn as a dash-dot line (— · — · —). The sketch of the optic itself may include direct references to some specifications, because it is necessary to indicate the surface(s) of the optical element to which each specification applies. The path of light through a complex element, such as a prism, may be indicated by the optical axis line. Angles are explicitly drawn and assigned a tolerance, and the angles between out-of-plane surfaces are referred to as *pyramidal angles*. Errors in these angles are called *pyramidal deviation errors*. Distances between elements of multielement drawings are specified by dimensions and assigned tolerances; for example, thickness values. Optical features such as aperture stops and physical features such as bezels may be included for reference.

Figure 3-2 shows an ISO 10110 drawing of a simple doublet lens. The remainder of this module will describe the specifications indicated in this drawing. Although drawings outline the required specifications, both optical designers and manufacturers realize that some specifications are more important than others. When describing a requirement on an optical drawing, the adjectives “normative,” “mandatory,” and “compulsory” all mean the same thing: the associated requirement must be met. Alternatively, some drawing notes may state alternatives for some specifications such as alternative glass materials. Of course, the manufacturer or vendor of an optical element can always take exception to any specification if it is impossible or cost prohibitive to meet. Such exceptions should be clearly communicated to the customer's optical designer or engineer who is responsible for the optical element.



Dimensions in Millimeters

Left Surface	Material	Middle Surface	Material	Right Surface
R 85 CX K $-1.5^{+0.25}_{+0.25}$ $Ø_E$ 45^{+5}_{+0} Chamfer: 0.25 - 0.75 (λ) AR 532, 1064 3/ 5(-) RMSi < 1 4/ 2.0 mr (6.9') 5/ 5x0.1;C5x0.2;L2x0.01;E0.2 6/ 95;1064;5 Note: damage test witness flats	GLASS: N-BAK4 N_d= $1.568827^{+0.003}_{+0.003}$ V_d= $55.98^{+0.5}_{+0.1}$ 0/ 10 1/ 5x0.1 2/ 2;4 Note: or S-BAL14	R 60 $Ø_E$ 45^{+5}_{+0} (λ) 3/ 5(2) 4/ 0.5 mr (1.7') 5/ 3x0.1;L0x0;E0.1 6/ 95;1064;5 Polished: Rq 0.001 0.001/0.100 Note: bond achromat with NOA63	GLASS: N-SF10 N_d= $1.728277^{+0.001}_{+0.001}$ V_d= $28.53^{+0.05}_{+0.05}$ 0/ 20 1/ 3x0.1 2/ 3;4 Note: or S-TIH10	R 175 CX $Ø_E$ 45^{+5}_{+0} Chamfer: 0.25 - 0.75 (λ) AR 532, 1064 3/ 5(-) RMSi < 1 4/ 2.0 mr (6.9') 5/ 5x0.1;C5x0.2;L2x0.01;E0.5 6/ 95;1064;5 Note: damage test witness fl

ISO Element Drawing Indications According to ISO 10110

DATE	SCALE	DRAWN	APPRV
2013-07-29	1.3000:1	Monacelli	OP-TEC
PROJECT/TITLE			
Quality Assurance of Precision Optics			
PART/DRAWING		REVISION	
ISO 10110 example		Module 3	

ISO 10110 example drawing.zmx
Configuration 1 of 1

Figure 3-2 *ISO 10110 drawing example: doublet lens*

Figure 3-3 shows a breakdown of the ISO 10110 drawing structure for each type of optical specification. There are 13 parts to an ISO 10110 drawing, as indicated in the table. Parts 2 through 7 and Part 13 are indicated by a number from 0 to 6 followed by a forward slash. These specifications will be indicated by a code that is called out in the ISO 10110 document. Each specification indicated like this will be clearly defined in this module. Other indications do not have an indicator (i.e., indication N/A), but their specifications will be written somewhere on the ISO 10110 drawing. For instance, general specifications (Part 1) include the nominal size, shape, and material of the optic. Data of a lens element (Part 10) may be a tabulation of points along the optical surface with respect to the drawing's origin. Aspheric surfaces (Part 12) may be specified by their conic constant among the general lens specifications in addition to a table of their surface coordinate data. Part 11 defines default tolerances: these defaults should be used if the optical designer does not specify tolerances.

Part	Title	Indication
1	General	N/A
2	Material Imperfections – Stress Birefringence	0/
3	Material Imperfections – Bubbles and Inclusions	1/
4	Material Imperfections – Inhomogeneity and Striae	2/
5	Surface Form Tolerances	3/
6	Centering Tolerances	4/
7	Surface Imperfection Tolerances	5/
8	Surface Texture	√
9	Surface Treatment and Coating	λ
10	Table Representing Data of a Lens Element	N/A
11	Non-toleranced Data	N/A
12	Aspheric Surfaces	N/A
17	Laser Irradiation Damage Threshold	6/

Figure 3-3 *ISO 10110 drawing specification structure*

Other Important Standards and Documents for Optics and Photonics

Throughout the history of precision optics fabrication, the United States military and other government organizations have played an important role in writing specification descriptions. Many U.S. military specifications, so called "MIL SPECS," are still commonly used to specify optics, though the international ISO 10110 Standard is steadily being adopted. Because they are still used, this text will reference some of the more common MIL SPECS. Their shortcomings will be evident when compared to the ISO 10110 Standard.

When processing precision optics, it is necessary to work with a variety of chemicals. To ensure safety while using the chemicals, precision optics technicians should familiarize themselves with the Material Safety Data Sheets (MSDS) for all chemicals. These sheets list the potential hazards of each chemical, particularly those that affect human health. Precision optics companies are required to maintain a log with the MSDS for every chemical uses to process their optics. Every employee should be familiar with the side effects of the chemicals the company uses.

When evaluating precision optics, technicians often need to work with high-intensity and laser light sources. Use of laser radiation hazards is regulated by the American National Standards Institute (ANSI) standard: ANSI Z136.1–Safe Use of Lasers, particularly Z136.5–*Safe Use of Lasers in Educational Institutions* and ANSI Z136.7–*Testing and Labeling of Laser Protective Equipment*. (The U.S. Food and Drug Administration (FDA) and Center for Devices and

Radiological Health (CDRH) also have guidelines that regulate invisible light sources, laser safety, and laser trade regulations.) These ANSI documents specify the source's optical parameters (nominal wavelength, maximum power output, etc.) and the required notifications and safety interlocks, as well as the protective equipment required during use. Protective equipment is usually used to protect against eye hazards; specific laser goggles are required for each type of laser. Laser goggles strongly attenuate the wavelength(s) of the high-intensity or laser source but still transmit a portion of visible light so that users can see while they are working. The laser goggle's *optical density* (OD) for each wavelength should be written directly on the goggle. OD is an integer value that indicates how strongly light is attenuated. Higher OD values mean more attenuation (lower transmission): an OD5 goggle attenuates ten times as much as an OD4 goggle, which attenuates ten times as much as an OD3 goggle, etc.

ISO 10110 Summary

To gain a thorough understanding of how precision optics are specified, this section presents a summary of each part of the ISO 10110 Standard. This is just a summary to introduce this standard. After reviewing this summary, we encourage you to review the full ISO 10110 Standard and study its content.

ISO 10110 Part 1: General Specifications

The general section of the ISO 101110 drawing specification includes a basic description of the dimensions and material of the precision optic. The part diameter follows the symbol ∅, for instance, as with tolerances ∅ 50^{+5}_{-0} for the nominally 50-mm diameter part shown in Figure 3-2. The effective diameter or clear aperture is similarly denoted by the symbol $\varnothing_e$; this is shown with tolerances as $\varnothing_e$ 45^{+5}_{-0} in the same figure. Thickness dimensions are assigned tolerances, measured along the optical centerline, and measured between arrowheads. Other length dimensions are also assigned tolerances and measured between arrowheads

Spherical radii of the optical surfaces are indicated simply by the letter *R* followed by the nominal radius value and a description of the shape: *CX* for convex or *CC* for concave surfaces. In Figure 3-2, the 85-, 60-, and 175 -mm and radii are indicated by "R 85 CX," "R 60," and "R 175 CX." (The internal radius may be viewed as either convex or concave.) Flat surfaces are indicated by $R\infty$ for their infinite radius, and *Rcyl* designates cylindrical surfaces. Cylindrical surfaces should be shown in two views. An arrow may point to the surface with the radius indicated.

Optical material specifications may be written in a few ways. Glasses may be called out by the glass code number or by the manufacturer's glass name, along with assigned tolerance values for the refractive index and Abbe number. The glass code has the refractive index and Abbe number built in, so there is no need to restate these nominal values, but their tolerances may be written directly. Metals and plastics should be called out with specific descriptions of their material type, along with processing notes. For example, heat-treated aluminum may be described as 6061 T6. In Figure 3-2, the glasses are called out by their Schott glass material names, N-BAK4 and N-SF10, and a note is also present to indicate that Ohara glasses S-BAL14 and S-TIH10, respectively, are acceptable alternatives.

The other common general specification indicates the chamfer (or bevel) size at the material's edges. This is written simply as "Chamfer:" followed by the maximum and minimum allowed chamfer sizes or by a nominal chamfer size with tolerances. In Figure 3-2, the chamfer sizes are indicated by “Chamfer 0.25 – 0.75,” with the unspecified units being in millimeters. In Figure 3-4, the photo on the left shows a technician adding an edge chamfer to a prism, and the photo on the right shows a prism that has a chamfered corner.

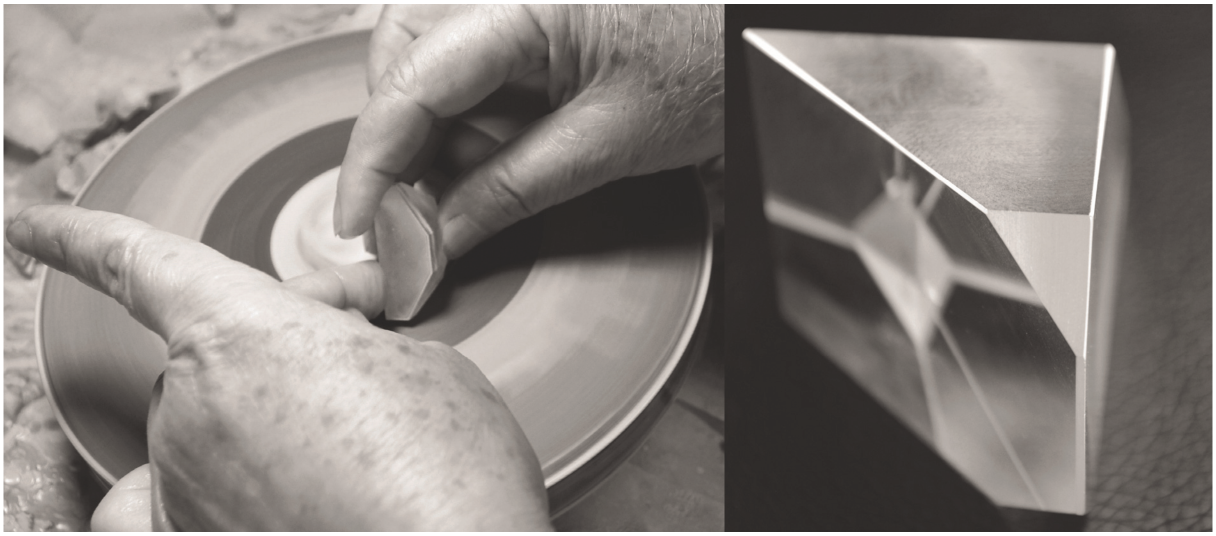


Figure 3-4 *This precision optics technician is adding a chamfer to the edge of a prism. The prism corner in the foreground of the right image has been chamfered*

ISO 10110 Part 2: Material Imperfections—Stress Birefringence

Precision optical substrates must possess certain physical qualities in order to be useful in an optical system. At a fundamental level, precision optics cannot be too fragile, flexible, brittle, volatile, or otherwise changeable. If an optic has any of these undesirable qualities, the performance of the entire optical system may be compromised. To discuss Part 2 of the ISO 10110 drawing standard, an understanding is required of stress-strain relationships in precision optics.

Application of *stress* (a force or load) onto any material causes it to *strain*, thereby physically deforming the part. It is essential to keep all optical surfaces from being strained. Stresses are often introduced into an optical material during processing. These stresses may be relieved thermally through a process called annealing; alternatively, they may be relieved mechanically, either by changing the shape of the optic to remove the load from the optical surface or by applying coating layers to uniformly balance the stress load. Even after fabrication, stress may be induced when precision optics are mounted. Figure 3-5 shows a very basic stress–strain plot. This figure is a plot of the stress as it is applied to a material all the way until it *fractures*. Under stress, materials first undergo an amount of *elastic deformation*, where they can exactly return to their initial shape. Then at higher stress levels, materials undergo *plastic deformation*, from which they can no longer return to normal. Stress beyond plastic deformation causes a material to fracture. Properly processed, coated, and mounted optics will have low stress, and the final product will not be measurably deformed (strained).

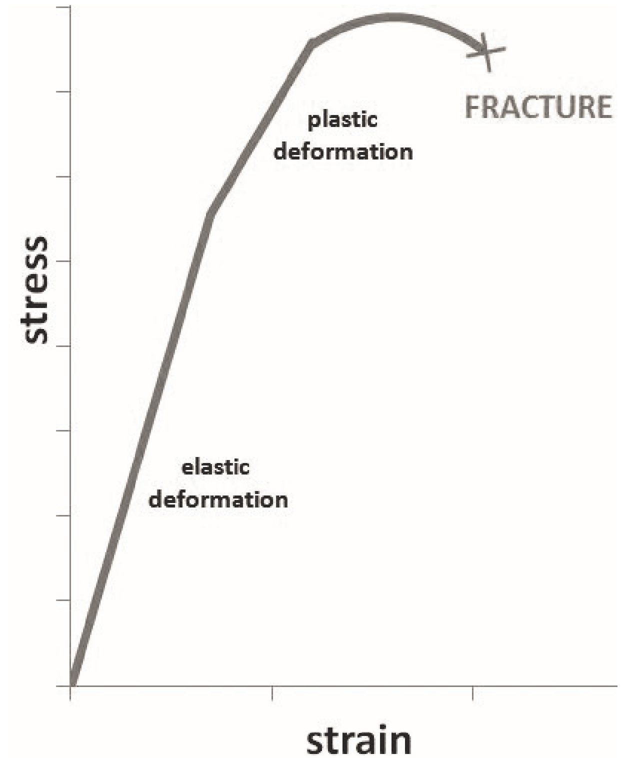


Figure 3-5 *Basic stress–strain curve, showing regions of elastic and plastic deformation as stress is applied, until the material ultimately fractures*

Stress within a transmissive optical component is called *internal stress*. Typically, internal stress in optics is not directly tested quantitatively because stress tests can be destructive and *witness samples* typically do not have the identical shape and size of the optic. However, internal stress may be indirectly measured by observing the material's birefringence. Crystals and some plastics are naturally, predictably *birefringent*, so their *birefringence* is not necessarily an indication of internal stress. However, most glasses and injection-molded plastics will demonstrate an unnatural birefringence if they are stressed during processing or mounting. For this reason, mechanical mounting stress is often modeled during the mechanical design phase of an optical system.

Internally stressing a material causes different colors to transmit through the material with different refractive indexes or, effectively, different speeds. This causes the different polarization states to be refracted at different angles, resulting in an instructive and attractive chromatic display that indicates the material's internal stress distribution. Figure 3-6 shows optics with and without these stress-induced chromatic displays. Internal stress is evident for the plastic optics, but not for the well-mounted glass optics. This attribute is known as the *photoelasticity* of the material.

The three images in Figure 3-6 show a variety of plastic and glass optical materials, some of them precision optics, under polarized light. The top image was taken with a single polarizer, the bottom left image was taken with the objects between two polarizers with parallel axes, and the bottom right image was taken with the objects between two polarizers with perpendicular axes. The colors appear due to a phenomenon known as the *photoelastic effect*. This system of polarizers on either side of the optics forms a *polariscope*, which, when calibrated, is used to quantitatively measure the internal stress in optical materials. In this example, the internal stress of the plastic optics is evident, even in the large precision plastic lens on the bottom. Note that there is little evidence of internal stress in the precision glass optics, and that the precision plastic magnifier lens and precision plastic prism have uniform internal stresses. This is due to the precision care taken during the injection-molding processes used in their formation.

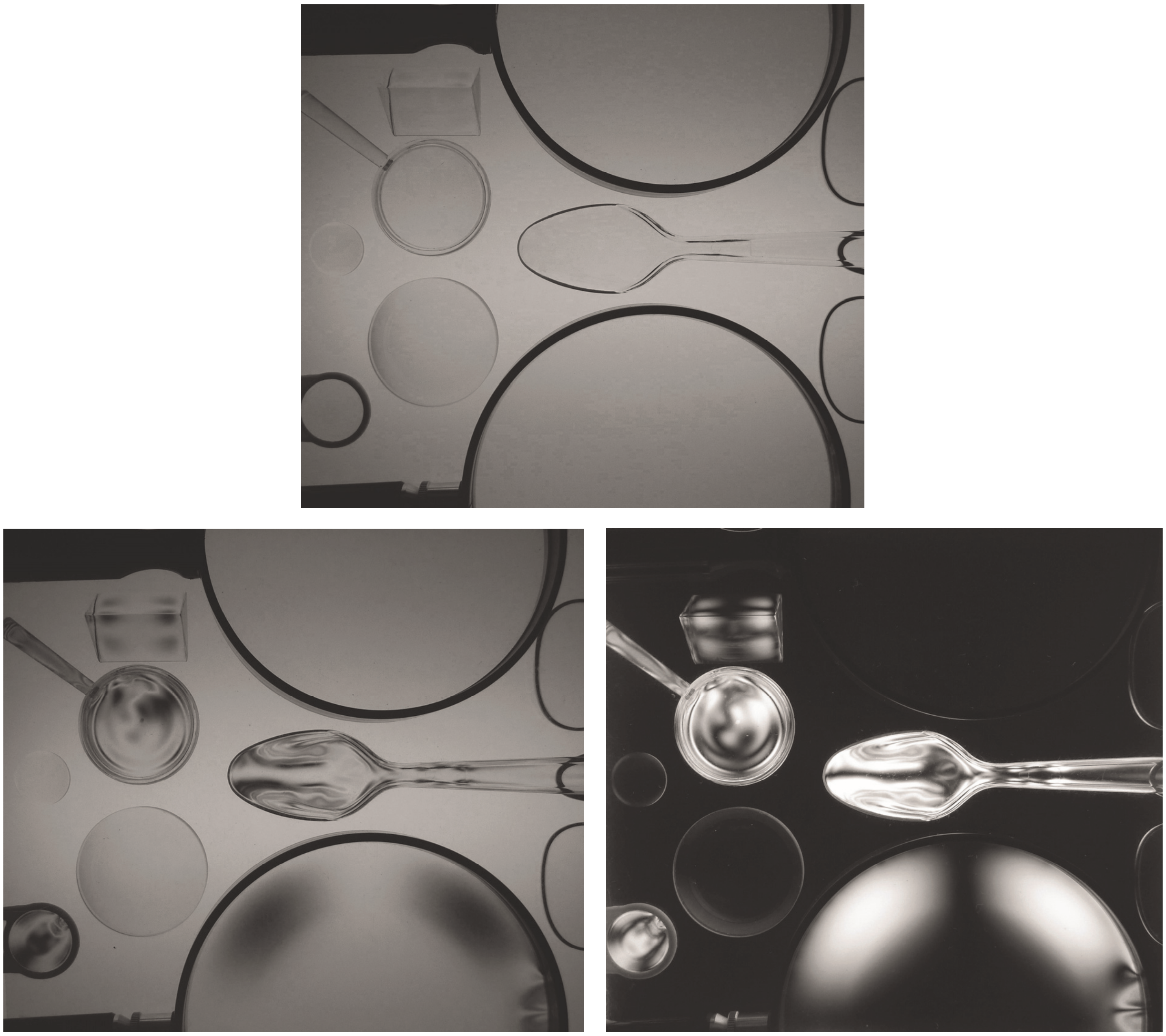


Figure 3-6 *Various optical materials under polarized light*

Polarimetry systems such as polariscopes are used in industry to measure stress birefringence of optical materials. Industrial polariscopes or polarimeters may be more complex in construction; they may include other phase-retarding components, such as waveplates, to obtain a precise measurement of the polarization of the input and output light.

ISO 10110 Part 2 (written ISO 10110-2) indicates stress birefringence using **0/** followed by the birefringence in units of nanometers of optical path difference (OPD) per physical path length in centimeters (nm/cm). That is, the OPD defines how much optical path is added as light travels through the physical thickness of the material. The OPD is caused by the refractive index differences (the birefringence) between different regions (say, region 1 has refractive index n_1 and region 2 has refractive index n_2) within the optical material. OPD is calculated using Equation 3-1, in which *d* is the thickness of the material.

$$OPD = d(n_1 - n_2) \tag{3-1}$$

Specifically, the OPD for stress birefringence comes from two material parameters related to internal stress, as given in Equation 3-2: σ is the residual stress (N/mm²), and β is the photoelastic constant in units of (m²/N).

$$OPD_{stress\ birefringence} = d \cdot \sigma \cdot \beta = d(n_1 - n_2) \tag{3-2}$$

Figure 3-7 shows typical values of stress birefringence for precision optics. These typical values range from 2 to 20 nanometers of OPD per centimeter of material thickness. The two glass lens materials in the example drawing of Figure 3-2 are specified to allow OPDs due to stress birefringence of 10 and 20 nm/cm.

ISO 10110 indication	permissible OPD due to stress birefringence per cm glass path [nm/cm]
0/ 2	≤2
0/ 4	4
0/ 5	5
0 /10	10
0/ 20	20
0/ -	no requirement

Figure 3-7 *Stress birefringence is given by the indicator 0/ followed by the OPD induced by stress*

ISO 10110 Part 3: Material Imperfections—Bubbles and Inclusions

Flaws within the bulk of an optical material—such as bubbles, grain boundaries, impurities, and inclusions—can diminish optical performance because they increase scatter and absorption. The simplest instrument used to assess internal flaws is the *loupe*, a fixed-focus magnifier that can be moved across a transmissive optical element to view flaws within the glass. This is an efficient way to check a part, but it does not provide a precision, quantitative assessment unless it is equipped with a calibrated reticle (a measurement scale) in its field of view. This scale must measure every flaw to fully assess the optic. Similarly, a *stereomicroscope* with a calibrated reticle may be used to assess the size and location of flaws within the bulk of an optical glass. This is the same technique that a jeweler uses to evaluate a gemstone's purity and quality. The stereomicroscope is similar to the loupe technique, but it may include a variable focus, so that different regions within the bulk of the glass can be viewed. The "stereo" aspect of this type of microscope allows the user to view internal flaws in three dimensions; this helps the technician gauge the character and orientation of flaws.

The *shadowgraph* technique that was covered in *QAPO Module 1*, Laboratory 1-A is a good way to quickly and inexpensively view the internal quality of a precision optical material by highlighting bubbles, inclusions, grain boundaries, some impurities, inhomogeneity, and striae.

This method involves projecting a diverging beam of coherent light onto a glass sample and observing the magnified flaws and refractive inhomogeneities in its internal structure. This technique easily leads to a visual qualitative evaluation, and if the observation geometry is calibrated, the shadowgraph technique may provide a quantitative assessment of striae size and location as well. A caliper located in the same plane as the sample being evaluated allows calibrated measurement of a witness sample's flaws.

Bubbles and inclusions have similar influences on the light that passes through an optical material. Therefore, they are specified jointly and are assessed using the preceding techniques. Their specification is indicated on an ISO 10110 drawing by **1/ N x A**, where **N** represents the maximum number of flaws allowed and **A** represents the size of the largest allowed flaw in units of millimeters. (The parameter **A** may also be interpreted as the square root of the largest area of the flaw in millimeters.) In Figure 3-2, the first glass is specified as **1/ 5 x 0.1** and the second as **1/ 3 x 0.1**, meaning that as many as five bubbles or inclusions are allowed in the first glass, and three are allowed in the second, while neither may have a flaw with a feature size greater than 0.1 mm.

ISO 10110 Part 4: Material Imperfections—Inhomogeneity and Striae

The shadowgraph technique is a good way to view inhomogeneity and striae. Along with a caliper, a homogeneity reference located in the same plane as the sample being evaluated allows quantitative assessment. However, more advanced instruments are available to directly measure the homogeneity and striae of optical materials. Figure 3-8 shows an industrial shadowgraph technique, along with images of low (grade A) and high (grade D) striae.

Figure 3-8 *The top image shows a shadowgraph being used in an industrial setting. The lower left image show almost no striae (class 5 / grade A), while the lower right images shows high striae (class 1 / grade D).*

The industry-standard tool used for direct quantitative inspection of homogeneity and striae is the *interferometer*. This powerful optical metrology system is most often used to assess optical surfaces, but since its light also passes through the bulk of a transmissive optic, interferometer vendors have designed software to evaluate homogeneity.

Interferometers operate by measuring the phase between two beams of coherent light. The measured phase is then used to calculate the OPD induced by the observed inhomogeneity. For a 10-mm thick sample (d = 10 mm), a refractive index difference (birefringence, $n_1 - n_2$) of only $3.0 \cdot 10^{-6}$ causes an OPD of 30 nm, as given by Equation 3-1. (This 30-nm threshold is an arbitrary value that is nevertheless significant because it is used to grade the material's striae.)

A diffuse optical surface is analyzed for homogeneity by subtracting two interferometric measurements: (1) a measurement of an empty interferometer cavity (between two optical flats), called a "cavity measurement," and (2) a measurement of the test optic within the same cavity called the "transmission measurement." Because the surfaces are diffuse, the test optic must be sandwiched between two additional flats, called "oil-ons." Oil-ons have polished external surfaces with a known and documented amount of error—this error is subtracted during the transmission measurement. The difference between the cavity measurement and the transmission measurement provides the material's homogeneity.

A test optic with precision-polished (specular) optical surfaces is analyzed in one of two ways: (1) by the "Phom" method, where both polished surfaces have a known wedge between them, or (2) by the "Flip" method where both polished surfaces are parallel planes. Each method requires the cavity and transmission measurements described above, as well as two additional measurements: one of the front surface and one of the rear surface. For both methods, the front surface is measured directly using the interferometer. Using the "Phom" method, the rear surface is measured through the front surface and the bulk of the material. For the "Flip" method, the rear surface is measured by flipping the optic upside down (by 180°). Software subtracts the four measurements (cavity, transmission, front surface, and rear surface) to provide the material's homogeneity.

ISO 10110-4 classifies optical inhomogeneity by the maximum permissible variation of refractive index within a part. Figure 3-9 shows the allowed variations for each inhomogeneity class. Similarly, Figure 3-10 shows the allowed values of "striae density causing an optical path difference of at least 30 nm" and each associated striae class. Since both inhomogeneity and striae are given by class numbers, the ISO 10110-4 designation is simple, **2/** followed by the homogeneity class, a semicolon, and the striae class. The example drawing in Figure 3-2 specifies class 2 as the homogeneity class of the first glass and class 3 for the second glass. Both glasses specify striae class 4.

If ISO 10110-4 is not used, striae may be called out under U.S. military specification MIL-G-174B, which compares the striae in an optical material under test to an unquantified reference that is held by certain agencies. The grades are written as **A**, **B**, **C**, and **D**, with **A** being the highest (tightest) specification, equivalent to ISO 10110-4 class 5.

Homogeneity Class	Maximum permissible variation of refractive index
0	$\pm 50 \cdot 10^{-6}$
1	$\pm 20 \cdot 10^{-6}$
2	$\pm 5 \cdot 10^{-6}$
3	$\pm 2 \cdot 10^{-6}$
4	$\pm 1 \cdot 10^{-6}$
5	$\pm 0.5 \cdot 10^{-6}$

Figure 3-9 *Homogeneity Class Standards for Precision Optical Materials, per Standard ISO 10110-4*

Striae Class	Density of striae causing an optical path difference of 30 nm
1	$\leq 10\%$
2	$\leq 5\%$
3	$\leq 2\%$
4	$\leq 1\%$
5	no visible striae

Figure 3-10 *Striae Class Standards for Precision Optical Materials, per Standard ISO 10110-4*

Other Material Imperfections and Material Properties Particular to Crystalline Optics

Other internal material flaws that are only specified in certain situations are discoloration and impurities. A variety of measurement techniques will reveal discoloration and impurities throughout the bulk of a witness sample, including some of the techniques already covered in this module and in *QAPO Module 2*. When compared to a reference, discoloration is apparent via the shadowgraph and microscopy techniques. Transmission and absorption measurements conducted during radiometric metrology will provide even more evidence of the root cause of the discoloration and impurities, because every material has a unique spectral “fingerprint”—its own unique reflection, transmission, and absorption spectrum. When comparing a known reference spectrum of the material being measured to the sample, inconsistencies can be correlated to the known spectral fingerprints of potential impurities. For example, if it is suspected that lead has contaminated a glass melt, a measurement of a sample of the glass may show absorption of light around 283 and 406 nm. Absorption at these particular wavelengths is a good indication that undesired lead is present in the glass.

Crystalline optical materials have a tendency to break along their atomic or molecular structure planes. This property is called *cleavage*, and it can result in flaws where cracks form along crystal planes. Careful handling and fabrication (cutting, grinding, etc.) helps ensure that cracks due to cleavage are never introduced into a precision crystalline optical element. More importantly, cleavage is the principle used to properly cut crystalline optics to their shape. The cut plane of a crystalline optic will be specified by its *Miller index*, which is a numeric description of its structure written as three or four numbers inside parentheses. For example, sapphire, a common optical crystal, and elemental semiconductor optics, such as silicon and germanium, are all typically cut along the (100) plane of their cubic crystal structure. That is, the atoms of these crystals are arranged in a cube, and they are cut along a side of the cube, rather than at an angle through a cube face.

It is particularly important to make cuts only along crystal planes because crystalline materials are naturally birefringent. Precise cuts orient the birefringence of the optic along a known direction. It is critical to the performance of an optical system to understand all potential causes of refraction for all polarizations of light. If an unexpected amount of refraction is observed for one polarization state but not another, the problem is likely to be birefringence.

ISO 10110 Part 5: Surface Form Tolerances

The surface of a precision optic is its defining characteristic. Jewels and gemstones may have flawless internal quality, but the shape of an element's surface—that is, the highs and lows across the surface's diameter—determines its performance in transmitting or reflecting light. Measurement of surface shape is best achieved by interferometry. A single surface may be evaluated for its *surface figure*, but a multiple-element optical system will be evaluated for its *transmitted wavefront error* (TWFE). Similarly, a single mirror surface may be evaluated for its *surface figure* or its *reflected wavefront error* (RWFE), and a system of mirrors may also be evaluated for its total RWFE. Both the TWFE and RWFE provide information for evaluating the surface shapes of the precision optics in an optical system and their compliance with design specifications. This evaluation uses the fringe pattern of an interferometer to determine the degree of this compliance.

For mirror surfaces, some optical designers specify surface figure error, while others specify RWFE. It is crucial to understand that for a single mirror, surface figure error equals half the RWFE because reflection means that errors are incurred twice.

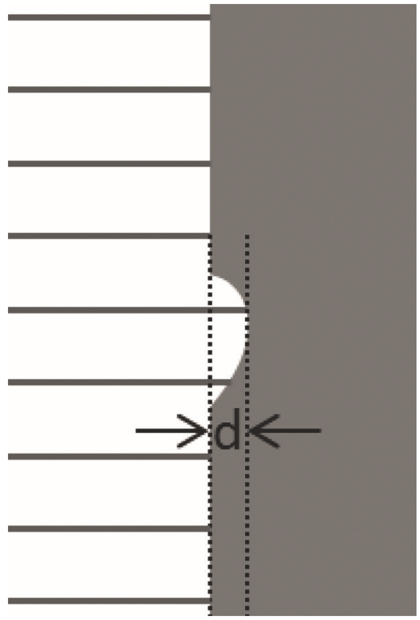


Figure 3-11 *The flat surface in the middle of this figure has an error in it of depth* **d***, so the light (represented by the lines on the left) will have to travel a distance of* **2d** *when reflected from this surface. This shows that RWFE is twice the surface figure error.*

As diagrammed in Figure 3-11, the surface on the right represents a plane mirror with an (exaggerated) error in it, and the lines on the left represent incident light. The surface figure only deviates from a plane mirror surface by a distance **d**, but the reflected wavefront error (RWFE) imposed on the light makes the light travel through the error over a distance equal to **2d**. This occurs because the RWFE imposed on the light includes a deviation of **d** while incident on the surface, and then imposes another deviation of **d** while reflecting back toward the source. RWFE values must be divided by two to yield surface figure values.

Surface figure or WFE measurements are the most common industrial application of an interferometer, typically via a technology known as Fizeau interferometry. To measure a single surface, such as the surface figure of a mirror or lens, both an interferometer and a calibrated reference optic are required. As depicted in Figure 3-12, the power of the interferometer's laser is split: it is partially transmitted through the reference optic, and it is partially reflected back into the interferometer by the reference optic. The portion that transmits through the reference optical element illuminates the full clear aperture (CA) of the optical element under test. The laser then reflects off the surface under test and reenters the interferometer, now traveling in the opposite direction. It is critical that the reference optic produces a beam with a shape that matches the curvature of the surface under test.

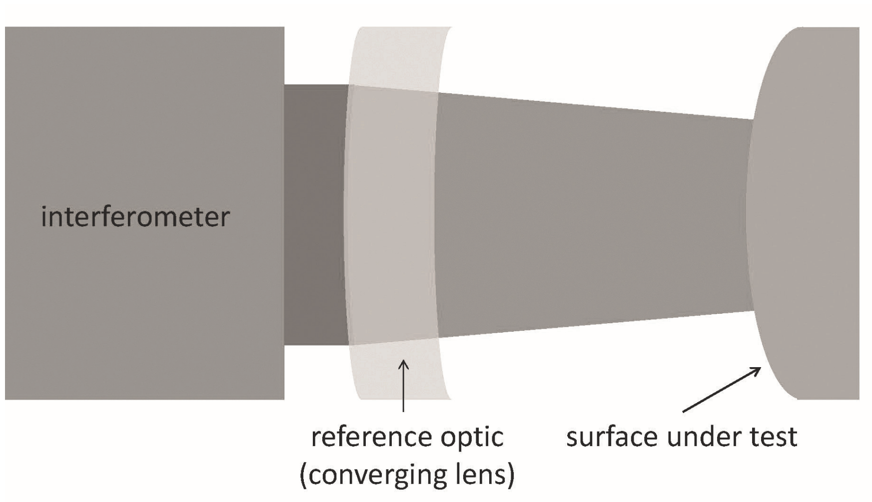


Figure 3-12 *An example of a setup for surface figure or RWFE measurement of a precision optic's convex surface*

The beam that sampled the surface under test and the beam reflected from the calibrated reference optic interfere at the interferometer's camera. Their interference produces a fringe pattern that is interpreted by the interferometer's software and converted to a detailed surface map showing the highs and lows of the precision optic's surface topography. Figure 3-13 shows a sample surface map. Departures from an ideal surface add *aberrations* to any light that interacts with the surface.

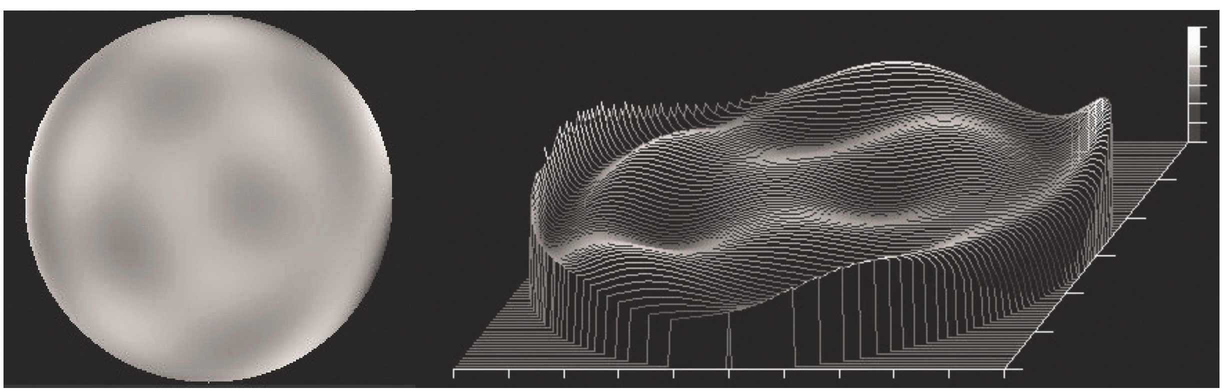


Figure 3-13 *An example of a surface map showing the highs and lows of a precision optical surface, as measured by an interferometer; plan view on the left, isometric view on the right*

A similar setup is used to test the TWFE of a lens or any complex, multielement optical system. For a TWFE measurement, the beam transmitted through the test optic or optical system needs to be directed back into the interferometer, exactly tracing the path through which it traversed the optical system. This is accomplished by placing a calibrated reference mirror at the output of the optical system. This mirror must be curved to match the curvature of the output light—that is, the focus of the optical system must coincide with the geometric center point of the reference mirror. This is referred to as *confocal* alignment. This reference mirror must be aligned to the optical system under test to ensure that light returns exactly along the path by which it arrived, perfectly reflecting the light back into the interferometer. In addition, reference mirrors must be calibrated prior to use so that their influence on the measurement can be removed mathematically. The reference mirror can be as complex as a custom aspherical mirror or as simple as a precision ball bearing made from a stable material such as silicon nitride.

It is essential to focus the optical system at the geometric center point of the reference mirror, not on the surface of the reference mirror. Light focused on the reference mirror's surface will, in fact, also return a beam into the interferometer that produces an interference pattern. This is often referred to as the "cat's eye" alignment. However, this is not the reflection that best represents the transmitted wavefront of the optical system, and it will not provide an accurate measurement of the TWFE.

Figure 3-14 illustrates an interferometric measurement of TWFE. The beam that transmitted through the entire multielement optical system under test and reflected back into the interferometer from the reference mirror, and the beam from the calibrated reference optic (such as a flat wedge) interfere at the interferometer's camera. Their interference produces a fringe pattern that is interpreted by the interferometer's software and converted into a detailed TWFE map for the precision optical system. However, this measurement must be appropriately scaled (divided) by a factor of two, because the light sampled the optical system twice: once going toward the mirror and once returning from the mirror.

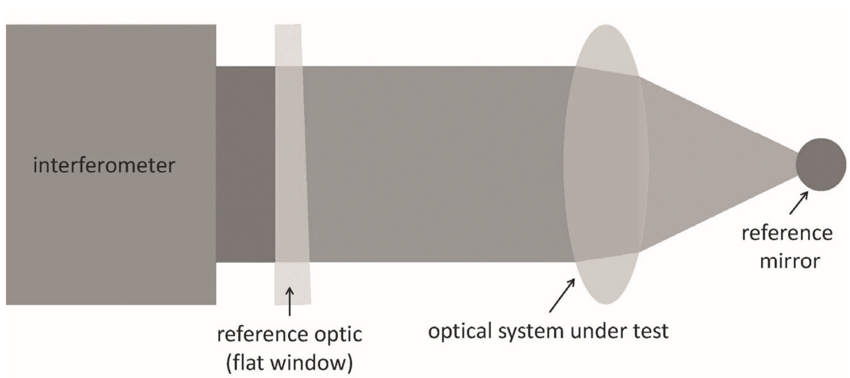


Figure 3-14 *An example of a setup for TWFE measurement of a precision lens or multielement optical system*

There are many different metrics used to assess the quality of the surface form. The two most common parameters are root-mean square (RMS) WFE and peak-to-valley (PV) WFE. The RMS value is a single statistical parameter that is calculated by taking a number of measurements of the surface. At each surface point sampled, a mean (average) is calculated. Then, each of the measured mean values are squared and all means are added together, and finally the square root of this sum reduces the measurement to a single value: the RMS WFE. The PV WFE is simply the difference between the maximum and minimum measured WFE values. As a loose rule of thumb, the PV specification is about five times the RMS specification.

It is necessary to understand all optical requirements in physical units—that is, units that can be physically measured. However, it is important to recognize that the units of the surface figure or WFE are often given in specifications as units of waves or fringes. These are frequently used units that often assume that the wavelength of the common interferometer is equal to 632.8 nm. However, specifications may assume the ISO 10110 default reference wavelength of 546.07 nm (per ISO Standard 7944). If this is the wavelength used, then one wave equals 546.07 nm and one fringe equals half this value. The potential for confusion is obvious, so assumptions should never be made when interpreting specifications. If the specifications' physical units are not clear, then confirm them with the optical designer or engineer. The reference wavelength should be specified on the optical drawing.

Surface figure, TWFE, or RWFE should be specified for a precision optic or optical assembly. Surface form specifications might be called out in explicit detail, as in the following examples, or they might be specified using the terms of ISO 10110 Standard Part 5.

FIGURE ERROR SHALL BE MEASURED OVER THE FULL CLEAR APERTURE TO BE LESS THAN 20 nm RMS AND 100 nm PV

TRANSMITTED WAVEFRONT ERROR OF THE ENTIRE OPTICAL ASSEMBLY SHALL BE MEASURED OVER ITS FULL CLEAR APERTURE TO BE LESS THAN 75 nm RMS AND 350 nm PV

Part 5 of ISO 10110 drawings uses the indicator **3/ A(B/C)**. The units for all parameters under ISO 10110-5 are **fringes**. The parameter **A** is the maximum allowed sagitta error, such that no more than **A** fringes shall be present when measuring the surface sag—that is, when comparing the surface to a flat test plate. If the surface's radius has an assigned tolerance, this parameter should be written as a dash (–), since these specifications would be redundant. The parameter **B** is the maximum allowed peak-to-valley (PV) irregularity of the surface; that is, no more than **B** fringes shall separate the highest high and the lowest low. The parameter **C** is the non-spherical, rotationally symmetric error, a parameter indicating a rotational symmetry of **C** fringes of the surface form error. Alternatively, this ISO 10110 indicator may specify the RMS surface form error, either with or without the parameters **A**, **B**, and **C**. RMS specifications are written in a number of ways. The indicator **3/– RMSt < D** indicates that the total RMS deviation from the nominal surface specified by the radius shall be less than **D** fringes. The indicator **3/– RMSi < D** indicates that the RMS irregularity shall be less than **D** fringes. The indicator **3/– RMSa < D** indicates an RMS symmetry of less than **D** fringes is required after spherical and rotationally symmetric irregularity have been removed. In all cases of RMS specification, the dash (–) may be replaced by the parameters **A(B/C)**, providing extreme detail on the surface form required.

Other PV and RMS forms may be specified, but these must be clearly defined since they are not officially part of the ISO10110-5 Standard. One such example is PVr (for PV robust), a parameter that combines the PV of the first 36 terms of a mathematical equation that describes the surface (called a Zernike polynomial) with the RMS of the residual surface error.

Note that the parameters **A**, **B**, **C**, and **D** have units of fringes per this specification. This is another cumbersome, nonphysical unit that requires that the wavelength **must** be specified on the drawing; otherwise, it is assumed to be 546.07 nm (per ISO 7944). The example drawing of Figure 3-2 specifies sagitta errors of less than 5 fringes and RMS irregularities of less than 1 fringe for the left and right surfaces (**3/ 5(—) RMSi < 1**). The middle surface is specified as **3/ 5(2)** to have less than 5 fringes of sagitta error (its radius is unspecified) with less than 2 fringes of PV irregularity.

ISO 10110 Part 6: Centering Tolerances

Centering of a precision optic is covered in Quality Assurance for Precision Optics Module 2, but should be defined here with respect to Part 6 of the ISO 10110 Standard. Centering tolerance is called out on ISO 10110 drawings by the indicator **4/** followed by the maximum allowed tolerance in either linear (millimeters) or angular (milliradians, mr, or arc minutes, ') units.

The example drawing in Figure 3-2 specifies centering the outer surfaces to have less than 2.0 mr (6.9') of angular error, while the middle surface is specified to have less than 0.5 mr (1.7') of angular error. In accordance with the ASME Drawing Standard Y14.5-2009 used in ISO 10110 drawings, centering errors are drawn with respect to a datum that is an explicitly defined reference surface.

ISO 10110 Part 7: Surface Imperfection Tolerances

A great deal of stress is applied to the optical surface of a precision optical element during the machining and grinding stages. These processes are intended to fracture away parts of the material that need to be removed to form the optical surface. This fracturing needs to be controllable and predictable so that the part is not permanently strained. A precision optic should be made of materials that are hard and durable. A material's *hardness* is often specified by an optical designer, and sometimes, even the hardness or type of abrasive is specified. The hardness is usually given in units of force per area, most commonly in kilograms of force per square millimeter (kg_f/mm^2). Optical materials range from around 300 kg_f/mm^2 (about that of tooth enamel) to 2000 kg_f/mm^2 (sapphire). Common glasses range from 400 to 800 kg_f/mm^2. Abrasives used to finish precision optics have hardness values that range from 800 to 2000 kg_f/mm^2.

Hardness is most often tested using an indentation hardness method known as the Knoop hardness test, in which a pyramid-shaped diamond point is pressed into a witness sample of the material. The load (a force), *L*, with which the diamond tip is pressed into the glass divided by the indentation area gives the material's hardness. Equation 3-3 is used to quantify a material's hardness based on the ASTM E384 Standard. There are different methods of evaluating the impression area, each method uses a different scaling factor to account for the shape of the diamond point. Typically, the impression area is measured as a scaling factor, *C*, for the tip size times the square of the impression's longest dimension, *d*:

$$Knoop\ Hardness \equiv HK = \frac{load\ [\mathrm{kg_f}]}{impression\ area\ [mm^2]} = \frac{L}{C \cdot d^2} \qquad (3\text{-}3)$$

Other types of hardness tests are also common. Results of the Vickers hardness test do not depend on the size of the indenter. The Rockwell hardness test is used to measure extremely hard materials. These tests each have their own code that corresponds to the hardness, such as Knoop 601 (a value for BK-7 glass), 80HV5 for the Vickers test (a value for iron), and M70 for the Rockwell test (a value for polycarbonate). Standard ISO 6508-1 is written for the Rockwell hardness of metals, and Standard ISO 2039-2 applies to the Rockwell hardness of plastics, including those metals and optics used in precision manufacturing. Testing to any of these standards may be required by the specifications designated by a precision optic designer.

Small pieces from the desired optical surface that do fracture during processing and handling are called *digs*—these are chips or pits in the optical surface itself. Digs are critical parameters for an optical designer to specify because digs scatter light, limit the optical throughput of a material, and can cause a crack that can later move through the bulk of the optic. *Fracture toughness* is the material property most specifically related to digs. This property is a material's ability to resist cracks, chips, and other forms of fracture. It has the (admittedly confusing) units of newtons per square meter times square-root meters $\left({}^{N}/_{m^2}\sqrt{m}\right)$. The fracture toughness of glass is on the order of 700,000 to 1,000,000 $\left({}^{N}/_{m^2}\sqrt{m}\right)$, while harder optical materials such as silicon carbide and sapphire are two to five times tougher. Both *brittle* and *ductile* materials can fracture. Materials with higher fracture toughness values are generally more ductile, and brittle materials have lower toughness.

The term *hardness* also relates to a material's surface hardness in terms of its *scratch resistance*. Scratches, like digs, are a critical specification of an optical element because scratches strongly and directionally scatter light, increase absorption, diminish transmission, allow laser damage, and affect the spectral performance of coatings. Scratches are caused by unwanted particles contained in the abrasives used during grinding, polishing, or cleaning. Many types of scratches may be formed, as shown in Figure 3-15. A good rule of thumb used to diagnose the cause of scratches is that the width of a scratch is 30% to 50% of the size of the unwanted particle that caused the scratch.

A tool called a *sclerometer* provides a measurement of a material's scratch resistance by incorporating a scratching element (such as a diamond tip) within a small, hand-held microscope. The scratching element applies a scratch with a known load to a witness sample, and the microscope measures the width of the scratch.

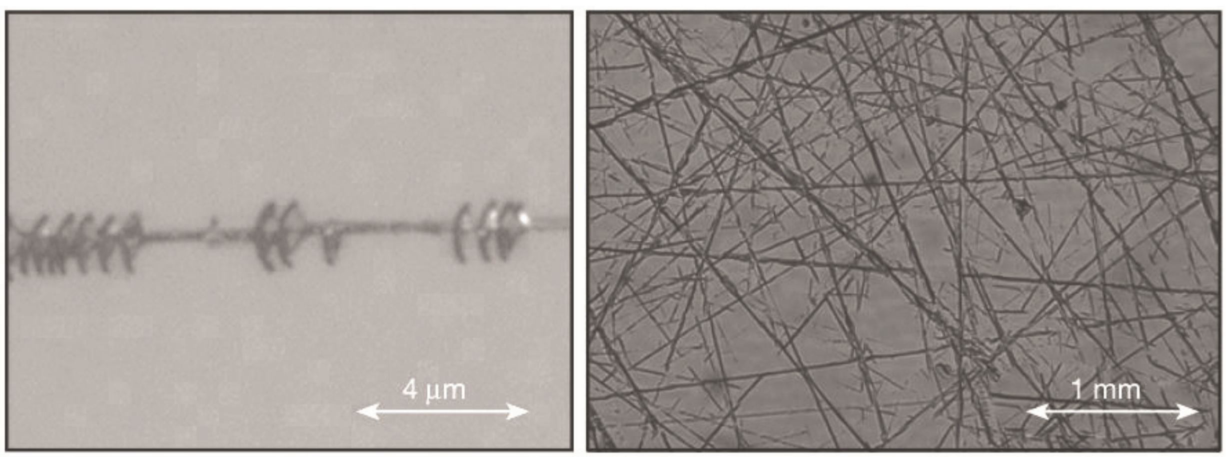


Figure 3-15 *Examples of scratches on precision optics, as seen under microscope inspection*

The number and size of scratches and digs on an optical surface defines the optical element's *surface quality*. ISO 10110-7 requires direct measurement of every scratch and dig. The indicator for surface imperfections is **5/ N x A** (similar to the specification for bubbles and inclusions), where **N** represents the maximum number of imperfections allowed and **A** represents the size of the largest allowed flaw in units of millimeters. (The parameter **A** may also be interpreted as the square root of the largest area of the flaw in millimeters.) If the letter **C** is under this indication, as in **5/ CN' x A'**, this specification applies to the imperfections in the optical coating. If the letter **L** is under this indication, as in **5/ LN'' x A''**, the number (**N''**) of scratches longer than 2 mm and their width (**A''**) is specified. Finally, if the letter **E** is under this indication, as in **5/ EA'''**, this specification applies to the allowable size of edge chips, in units of millimeters. These quality specifications—for the optical substrate, its coating, long scratches, and edge chips—may all be included under this indication, written as **5/ N x A; CN' x A'; LN'' x A''; EA'''**.

The example drawing in Figure 3-2 specifies **5/ 5x0.10; C5x0.20; L2x0.01; E0.50** for the outer surfaces and **5/ 3x0.10; L0x0; E0.10** for the middle surface. Breaking this down, this specifies no more than 5 flaws in the substrate and 5 in the coating of the outer surfaces, and that the coating flaws may be twice as large (0.2 mm) as the substrate flaws (0.1 mm). The inner surface may have no more than 3 flaws that extend less than 0.10 mm. Long scratches are not allowed on the inner surface, and 2 are allowed on the outer surface, but they must be no wider than 0.01 mm. Larger edge chips measuring no more than 0.50 mm are allowed on the outer surfaces, while smaller 0.20-mm edge chips are allowed on the inner surface. This is a very quantitative and explicit specification of the surface imperfections.

If ISO 10110-7 is not used, scratch–dig specifications may be called out using U.S. Military Specification MIL-PRF-13830B, which is a subjective visibility standard. This requires the precision optics technician to compare the scratches and digs in an optical material under test to an unquantified reference sample set. Different versions of this set are held by certain agencies and reproduced by some optics vendors. This qualitative reference set is used to assign a grade to the scratches and digs present, using only the unaided eye and bright lighting. Specifications written using this MIL SPEC include two numbers separated by a hyphen, such as 40-20 or 10-5. These numbers loosely relate to the quantity, size, and character of the scratches and digs on the optical surface, with lower numbers indicating fewer, smaller scratches and digs, but under this MIL SPEC, there is no exact quantification. Despite the unambiguous, quantitative clarity of the ISO 10110-7 surface imperfection specification, the qualitative MIL SPEC technique of specifying surface quality remains popular.

ISO 10110 Part 8: Surface Texture

An optical material's surface texture or *surface finish* generally describes its *roughness*, that is, its microscopic structure. This specification is similar to the surface form, but it concerns surface structure with much higher spatial frequencies—the surface’s highs and lows on a microscopic scale. Roughness includes engineered effects, such as fabrication tooling marks and contours created by the abrasives used during polishing, as well as the natural three-dimensional topography of the surface. When technicians measure roughness, they evaluate the features’ size, spatial frequency, and directionality. Roughness assessment can help improve fabrication processes, but it is also important in the final application of the precision optic, because it can cause imaging problems due to scatter, particularly when the structure of the roughness is highly directional. A common example of this is the residual surface roughness after single-point diamond turning (SPDT) a mirror. In this fabrication method, the technician moves a diamond tip in a spiral over the surface of the substrate to remove the material. This creates a tiny, residual spiral groove in the substrate. An image through this system is likely to have a halo around bright points, due to diffraction by these grooves. Similarly, if a lens is polished by moving the abrasive in only one direction, the surface will have linear scratches on a microscopic level. These scratches can cause similar scattering and diffractive effects in application.

To measure roughness, a technician probes the surface using either a contact or a noncontact probe. Regardless of the type of probe, roughness is reported as a statistical average or *root-mean square* (RMS) value of many samples within the CA of the precision optic. A good rule of thumb is that the sampled region must be at least ten times as large as the size of the largest feature being measured, and the measurement resolution must sample the smallest features five to ten times. The measurement resolution should be a fraction of the spatial separation between the smallest evenly spaced features on the optic.

Mechanical profilers contact the surface by dragging a fine point (called a stylus) in a line over the surface. The deflection of the cantilevered stylus is calibrated to output the depth of each deflection, thereby mapping the surface structure—the roughness—along the line measured. (It is like a phonograph needle reading a record.) The position of the stylus is usually sensed by reflecting a laser off its cantilever and sensing the laser output with a calibrated detector.

An obvious noncontact method to view any microscopic surface is microscopy. However, powerful optical or even electron-beam microscopes only produce two-dimensional images, which provide no depth or roughness information. Again, enter interferometry. Systems called *optical profilers* measure three-dimensional surface roughness as depicted in Figure 3-16. They function in a manner similar to a microscope: A probe beam of coherent light is focused onto a region of the sample. This probe beam is split and directed to a calibrated reference mirror. This creates two beams, one reflecting from the witness sample and the other from the reference mirror. These two beams interfere on a detector. At the detector, the contrast of the fringe pattern provides information about the surface roughness: rougher surfaces deviate more from the ideally smooth reference, causing less contrast in the fringes. As the probe beam is scanned over the sample surface, a 3D surface topography map is constructed. If the coatings are transmissive to the probe beam, this technique can be used to measure the roughness of subsurface layers. Commercial systems can measure roughness with resolutions of less than 0.01 nanometers!

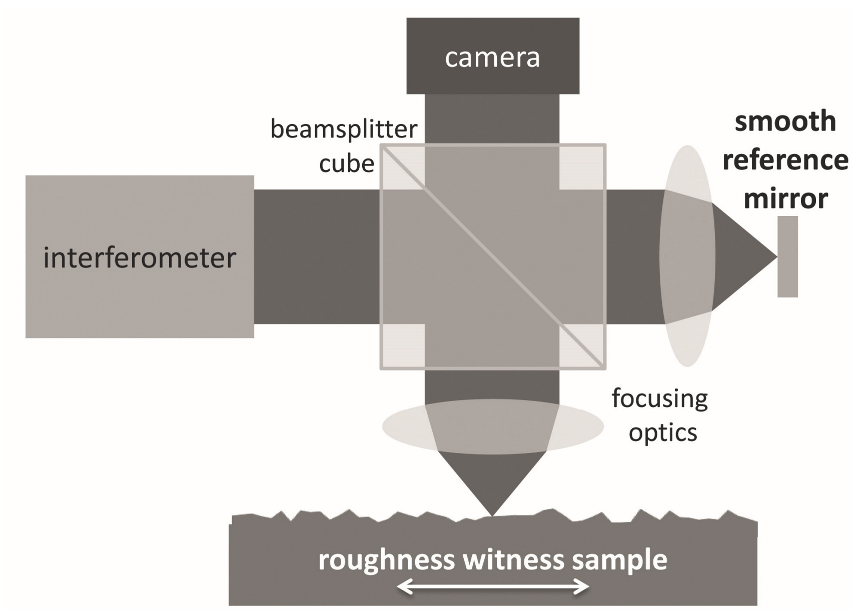


Figure 3-16 *An interferometric and optical profile has two beam paths: one beam measures a smooth reference mirror surface, and the other measures a witness sample surface. The resulting interferogram at each sample point provides a measure of the witness sample roughness.*

Part 8 of the ISO 10110 Standard specifies surface texture. The indication for this specification is unique: it resembles a stylus and points to the optical surface. Figure 3-17 shows the layout of the parameters of this specification with respect to the symbol. There are three parameters: (1) type of texture: **G** for a ground (coarse) surface and **P** for a polished surface; (2) type of measurement: usually the **RMS** surface roughness, indicated by **Rq**, followed by the specified roughness value in micrometers; and (3) scan resolution and scan length in units of millimeters. The type of measurement may also be specified as power spectral density (**PSD**). This would require a plot or tabulated data of the roughness magnitude as a function of spatial frequency.

Figure 3-2 indicates surface texture for the outer surfaces, specifying an RMS roughness (**Rq**) of 0.001 millimeters (1 µm), as measured with a scan resolution of 1 micrometer over a 100-micrometer scan length.

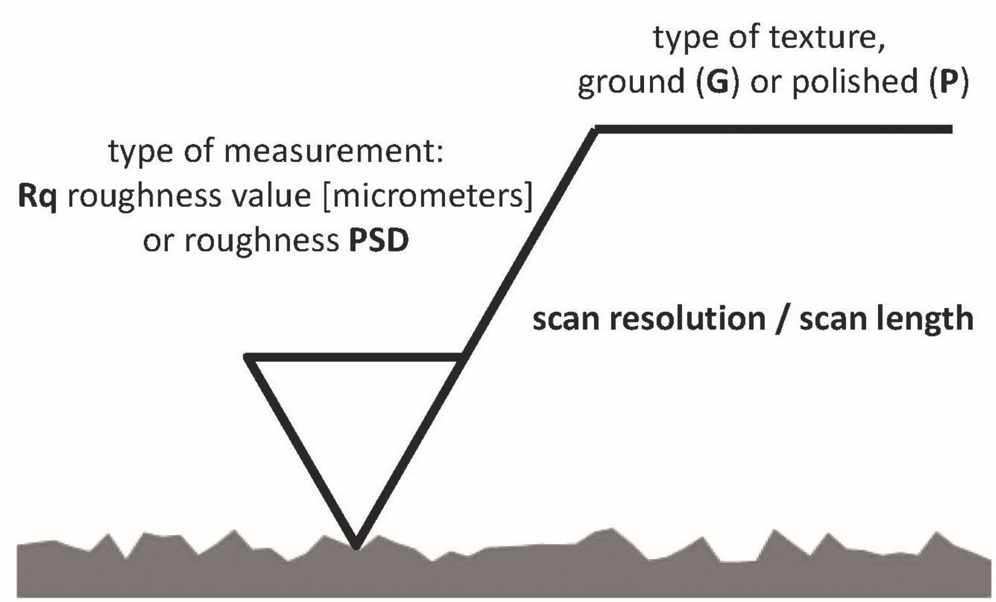


Figure 3-17 *Per ISO 10110-8, this is the indicator for surface texture and its parameters*

ISO 10110 Part 9: Surface Treatment and Coating

When the application of optical coatings was covered in *QAPO Module 1*, it was apparent that there are many techniques used to apply them, and that there are many reasons to coat optics. *QAPO Module 2* discussed the use of spectroradiometry and spectroscopy to measure the radiometric properties of optical coatings, including coating reflectivity, transmissivity, and absorptivity measurements. ISO Standard 9211 covers coating specifications in detail. All coatings should be deposited to cover an area slightly larger than the clear aperture of the optical element, unless otherwise specified. To promote coating adhesion, particularly for metal coatings and on metal mirrors, some coatings are applied to roll over the edge of the optical element. Optical coatings should never have obvious flakes, peels, cracks, blisters, streaks, stains, pores, or cloudiness.

When an optical designer specifies a coating on a drawing, the radiometric performance of the coating may be explicit, stating the desired spectral shape of the coating's desired reflectivity or transmissivity spectrum, and perhaps even including a theoretical curve. The designer might even specify a particular vendor's coating process. Alternatively, the coating specification may be general, simply reading "coat HR VIS" (HR indicates that this coating should be highly reflecting for VIS (visible) light, nominally ranging from 400 to 700 nm). An explicit coating specification might read like this example:

HIGH TRANSMISSION COAT THE CLEAR APERTURES OF ALL SURFACES
AVERAGE REFLECTIVITY <0.5% PER SURFACE FROM 500 to 700 nm,
<1.0% PER SURFACE FROM 700 to 1100 nm, <0.1% PER SURFACE AT 532 and 633 nm

Surface treatments are not limited to coatings that enhance radiometric performance. Some surfaces are specified to be painted to protect the surface or prevent stray light and ghost images. In these situations, a particular paint from a particular vendor may be specified, or the specification may simply read “protective paint surface.” Some paints are made especially to function as optical blacks, and these may be explicitly called out. It is important to note that not all black-colored paints are optically black—that is, absorbing—for all wavelengths.

If possible, to protect a finished precision optic, a permanent protective outer coating layer is applied to cover the underlying coating layers that enhance optical performance—these protective layers usually do not impact the optical signature. Protective coating materials include silicon monoxide (SiO), aluminum oxide (Al_2O_3), or thorium tetrafluoride (ThF_4), among others. These coatings are permanently part of the optic and should not be confused with the sacrificial protective paints and waxes that are used during fabrication.

In all cases, ISO 10110 drawings indicate the surfaces to be coated or painted by the letter λ in a circle: λ. The circle of this indication should touch the surface to be coated in the drawing, and the specification’s details will be listed in a table that corresponds to the surface. In Figure 3-2, the coating is specified as: λ**AR 532, 1064**, indicating that the coating shall be antireflection (AR) for wavelengths of 532 and 1064 nm.

ISO 10110 Part 10: Table Representing Data of a Lens Element and ISO 10110 Part 12: Aspheric Surfaces

It is often useful for the optical manufacturer to have explicit data in a tabular format that represents the physical coordinates of an optical element’s surface with respect to a specific datum (reference point). This tabular data can be entered into a computer numeric controlled (CNC) milling machine to fabricate the blank of the optical element to near-net shape. The drawing in Figure 3-2 does not include a table with lens surface coordinate data, but the drawing does tabulate all specifications for this lens element.

A tabulation of lens surface coordinates is very helpful if the optical element has any asphere surfaces. Also accompanying this table may be a sag equation that shows the mathematical form of the asphere intended in the optical design, including the conic constant and any higher-order asphere terms. It is important to be familiar with an equation that describes an aspheric surface, so one is shown in Equation 3-4. In this sag equation, R is the surface’s radius of curvature at its vertex, r is its radial coordinate, k is the conic constant, and a_i are higher-order asphere terms.

$$sag \equiv z_{conic}(r) = \frac{r^2}{R\left(1+\sqrt{1-(k+1)\frac{r^2}{R^2}}\right)} + a_4 \mathrm{r}^4 + a_6 \mathrm{r}^6 + a_8 \mathrm{r}^8 + a_{10} \mathrm{r}^{10} \tag{3-4}$$

ISO 10110 Part 11: Specifications for Non-toleranced Data

Tolerances for some parameters may be omitted from optical drawings. If so, Part 11 of the ISO 10110 Standard does define default values for data with no tolerance specified. These default values are listed in Figure 3-18. Note that most tolerances listed here scale with the diameter of the part. Regardless of this section of the standard, it is good practice in any technical field to confirm with the designer any unclear or non-toleranced aspects of a drawing.

Property	Range of maximum (diagonal) dimension of the part [mm]			
	up to 10	10 to 30	30 to 100	100 to 300
Edge length, diameter [mm]	± 0.2	± 0.5	± 1.0	± 1.5
Thickness [mm]	± 0.1	± 0.2	± 0.4	± 0.8
Ange deviaion of prism and plate	± 30'	± 30'	± 30'	± 30'
Width of protective chamfer [mm]	0.1 to 0.3	0.2 to 0.5	0.3 to 0.8	0.5 to 1.6
Stress birefringence [nm/mm] (per ISO 10110-2)	0/ 20	0/ 20	-	-
Bubbles and inclusions (per ISO 10110-3)	1/ 3x0.16	1/ 5x0.25	1/ 5x0.40	1/ 5x0.63
Inhomogeneity and striae (per ISO 10110-4)	2/ 1;1	2/ 1;1	-	-
Surface form tolerances (per ISO 10110-5)	3/ 5(1)	3/ 10(2)	3/ 10(2)	3/ 10(2)
Centering tolerances (per ISO 10110-6)	4/ 30'	4/ 20'	4/ 10'	4/ 10'
Surface imperfection tolerances (per ISO 10110-7)	5/ 3x0.16	5/ 5x0.25	5/ 5x0.40	5/ 5x0.63

Figure 3-18 *ISO 10110-11 drawing specifications for non-toleranced data*

ISO 10110 Part 17: Laser Irradiation Damage Threshold

Part 17 of the ISO 10110 Standard calls out a particular type of durability specification for the optical coating: the durability required for use with high-irradiance lasers. (Environmental coating durability specifications will be covered in the next section.) In some optical systems, the lasers used are powerful enough to damage the optical coatings and their substrates, even if the laser beams are unfocused. In systems that require increased laser irradiance (power per unit area) on the optics, laser damage is a particular concern.

Laser damage is tested using witness samples because these are often destructive tests: they irradiate the coated substrates to the point of physical damage. To test a part's laser damage threshold, the witness sample is located in the path of a high-energy laser beam, and the technician incrementally increases the beam's power, checking the integrity of the coating between each test. When the coating shows damage, the power and irradiance of the test laser is measured, and that is declared the coating's laser damage threshold. Either pulsed or continuous wave (CW) lasers may be required for these tests, depending on the application of the optical element. Therefore, the specification must call out the type and parameters of the laser to be used during the laser damage threshold test.

Not all optical elements will specify laser damage threshold, because not all optics will be used with lasers. If an optical element does require laser use, laser damage threshold is specified on optical drawings in accordance with ISO 10110-17, indicated by **6/** followed by either the energy density threshold, $\mathbf{H_{th}}$, in units of joules per square centimeters [J/cm²] for pulsed lasers, or irradiance (power density) threshold, $\mathbf{E_{th}}$, in units of watts per square centimeters [W/cm²] for CW lasers. These thresholds are followed by the laser wavelength and beam parameters. For pulsed lasers, the specification would read **6/** $\mathbf{H_{th}; \lambda; \ell_p; f_p; n_{ts} \times n_p}$. The wavelength of the laser, $\boldsymbol{\lambda}$, is followed by the pulse length (duration), $\boldsymbol{\ell_p}$; then the pulse frequency (laser repetition rate), $\mathbf{f_p}$. The final parameters are $\mathbf{n_{ts}}$ and $\mathbf{n_p}$: $\mathbf{n_{ts}}$ states the number of sites (locations) to test across the optical element, and $\mathbf{n_p}$ indicates the number of pulses with which each site should be irradiated. For CW lasers, the specification would read **6/** $\mathbf{E_{th}; \lambda; n_{ts}}$, with irradiance threshold followed by the laser wavelength and the number of test sites. Test sites should be uniformly spaced across the clear aperture of the witness samples to account for coating nonuniformities. The drawing in Figure 3-2 specifies laser damage thresholds for all surfaces: this lens is likely to be used in a 1064-nm CW laser system with a maximum irradiance of 95 W/cm². It is specified to be tested at five sites across its clear aperture.

Environmental, Thermal, and Other Important Considerations for Optical Elements and Coatings

All of the previously presented material properties are actually functions of the temperature and pressure to which the precision optical element is exposed during fabrication, coating, and application. It is important to understand that optical system performance will be affected by the operational temperature and pressure because all of the aforementioned material properties may change due to these effects. (ISO 10110 drawings use 20°C as the default temperature and atmospheric pressure as the default pressure, but designers may state other temperatures on the drawing.) Even the size of an optic may change in dimension due to the material's *coefficient of thermal expansion* (CTE), in units of per degree Celsius (/°C). In fact, everything changes size and shape with temperature. Most materials expand when heated. Common linear (dimensional) coefficients of thermal expansion for optical glasses range from $0.02 \cdot 10^{-6}$ to $8.5 \cdot 10^{-6}$/°C, and that of silicon is $2.6 \cdot 10^{-6}$/°C. The common mirror and lens mount material 6061 aluminum has a CTE of $23 \cdot 10^{-6}$/°C, and beryllium, another optical mirror material, has a CTE of $11.3 \cdot 10^{-6}$/°C. It should be evident that the temperature range of operation must be considered when placing various materials in contact with one another within an optical system. When materials change size in optical systems, the results can be damaging not only to the optical performance (because light takes a new path through optics of a new shape), but also because glass elements might change size at a different rate than their metal mounts. Compare the CTE of aluminum (a common mount material) to that of glass—aluminum changes size at 3 to 1000 times the rate of glass! This can cause extreme stress to the glass, causing it to crack, shatter, or come free from its mount. To prevent this, it is important to understand the rates and directions that an optical material might change form as its temperature changes.

Extremely rapid changes in temperature may result in *thermal shock*. This is the cause of many cracked windows and shattered glass cooking pans. Even if thermal annealing processes are properly performed during fabrication, the optical material may quickly become internally stressed, leading to failure by fracture. This phenomenon is not unique to glass. Metals and plastics experience it as well.

Optical materials should be stable over the duration of their use while withstanding different chemical environments. An optical material and the materials holding the optics must not react, change form, or decompose when located in the environment of the optic's intended application. In some situations, materials may spontaneously shift form. Any form shift of a precision optical element may be detrimental to its optical performance, and the optic may need to be refinished. Metal mirrors might change shape while being used in the field even years after the final precision polish has been completed.

The ideal environments for evaluating, handling, and packaging optics are cleanrooms and clean flowbenches. These are areas from which particulates are removed by flowing the air through high-efficiency filters. This creates positive pressure with respect to the outside environment, pushing any potential contaminants out of the area or into the filter, where they are trapped. This keeps the optics clean and free of particulate contamination. Cleanliness standards for cleanrooms, known as *cleanliness classes* (per Standard ISO 14644-1, formerly Federal Standard 209C) are given in Figure 3-19.

Standard ISO 14644-1	cleanroom class designation		number of particles per cubic meter for each particle size given					
	Metric	English	0.1 micrometer-sized particles	0.2 micrometer-sized particles	0.3 micrometer-sized particles	0.5 micrometer-sized particles	1.0 micrometer-sized particles	5.0 micrometer-sized particles
ISO 1			10	2				
ISO 2			100	24	10	4		
ISO 3	M1.5	1	1,000	237	102	35	8	
ISO 4	M2.5	10	10,000	2,370	1,020	352	83	
ISO 5	M3.5	100	100,000	23,700	10,200	3,520	832	29
ISO 6	M4.5	1,000	1,000,000	237,000	102,000	35,200	8,320	293
ISO 7	M5.5	10,000				352,000	83,200	2,930
ISO 8	M6.5	100,000				3,520,000	832,000	29,300
ISO 9						35,200,000	8,320,000	293,000

Figure 3-19 *Cleanroom Cleanliness Standards for Precision Optics, per ISO Standard 14644-1*

It is critical to monitor and measure the cleanliness of the area in which precision optics are handled prior to opening their protective containers. Even within a cleanroom, precision optics require proper packaging. Good materials in which optics may be wrapped include lint-free cloths, lens tissue, soft synthetic cloths, cotton cloths, cheesecloth, and molded plastic containers that only contact the optic's periphery. An optic should never react with its mounting or packaging material. One of the worst packaging materials that is frequently used is foam. Over time, foams decompose and may adhere to optical surfaces, requiring cleaning and packaging replacement.

Special handling equipment is required to keep human biology (hair, dead skin cells, skin oils, saliva, etc.) and air particulates off optical surfaces. Powder-free gloves, usually made of nitrile or latex, should be used whenever handling precision optics to prevent contamination by oils, skin, and hair on the hands. Additionally, a surgical facemask prevents moisture from the mouth and nose from escaping onto the optical surfaces. A lab coat is required in most optics shops. In fact, a full cleanroom suit that covers all hair, clothing, and shoes (called a "bunny suit") may be required for applications of extreme cleanliness.

When an optical element is contaminated, it must be cleaned. Optical elements are cleaned using clean, dry air sprays or liquid chemical solvents such as deionized water, alcohol (ethyl alcohol, methanol, isopropanol), acetone, methyl ethyl ketone (MEK), or even liquid detergents. Lint-free cloths or lens tissues are used to apply these chemicals. Many solvents can deteriorate optical coatings, so it is extremely important to learn from the coating vendor the best methods of cleaning a particular optical element. In some cases, a precision optic cannot be cleaned without destroying its coating or structure.

Cleaner optics are always better optics because they limit scatter and potential damage caused by high-energy light. (Even if an optic passes laser-damage testing, a piece of dust or dirt on an optic can absorb laser light, forming a hot spot that damages the coating.) Most optics specifications call out exact cleanliness requirements that include everything from the allowable sizes and quantity of contaminants on the surface of the precision optical element to the allowable sizes and quantity of particles in the room where the optic is precision cleaned and coated. Surface contaminants are considered *nonvolatile residue* (NVR). NVR is defined by Standard MIL-1246 as the material remaining after evaporation of a liquid. It is defined as the mass of the contaminants per area of the surface, with units of $\mu g/mm^2$. Cleanliness standards for optical surfaces, known as *cleanliness levels* (per MIL-1246C) are given in Figure 3-20.

NVR Surface Cleanliness Level	Surface Contaminant Limit [$\mu g/mm^2$]
A/100	0.01
A/SO	0.02
A/20	0.05
A/10	0.1
A/S	0.2
A/2	0.5
A	1.0
B	2.0
C	3.0
D	4.0
E	5.0

Figure 3-20 *Cleanliness Standards for Optical Surfaces, per Standard MIL-1246C*

While many optics are used in pristine labs and sealed assemblies, some optics are exposed to harsh environments such as sea water, turbulent airflow, or outer space. Chemicals and radiation in these environments can react with or corrode the material of the optic, actually altering the chemistry of the exposed optical surface. Glass corrosion (also known as “glass disease” or “sick glass”) is caused by glass’s slight solubility in water. (It is often seen in old drinking glasses.) For precision optics, any material degradation due to chemical reactions may diminish transmission and increase absorption and scatter. The *durability* of a thin film coating is specified by the optical designer based on the conditions to which the optical element will be exposed. A coating durability specification might include the following information:

COATING TO MEET THE ENVIRONMENTAL REQUIREMENTS OF MIL-C-675
FOR ADHERENCE, MODERATE ABRASION, AND HUMIDITY,
TESTING MAY BE PERFORMED ON A WITNESS SAMPLE

Specifications like these often call out a series of environmental tests with reference to a durability specification such as MIL-C-675. These tests might include abrasion, adhesion, humidity/fog exposure, or salt/sea water solubility. These tests are conducted on witness samples because they may be destructive. Section 4.5 of MIL-C-675 explains these tests, but the optical drawing may explicitly describe the environmental tests required. Abrasion tests use a rubber eraser, rubber pumice, or another abrasive material to physically scuff the surface of the optical element. Tape tests are used to characterize adhesion: a piece of cellophane tape is applied directly to the surface and removed—if the coating remains undamaged, it passes the test. Water-based tests, such as humidity and solubility, require an optics shop to subject the parts to elevated temperatures and humidity levels. These are conducted using environmental chambers such as those shown in Figure 3-21.

Figure 3-21 *Environmental chambers like these are used to test precision optics by changing the ambient temperature and pressure and by simulating the conditions, such as humidity and salinity, of their application*

Finally, some optical materials must also have particular electrical properties. The most common examples of electrically active optical materials are conductive indium tin oxide (ITO) and aluminum zinc oxide (AZO). Thin films of these materials are used within the layers of sheet glass that compose touch-screen displays and antistatic cleanroom windows. Glasses and crystals are excellent electrical insulators, so including a conductive layer allows the material to change capacitance as it is touched (pressed). Specifications may require electrical tests, such as resistivity or capacity measurements, to be performed on the finished precision optic.

Mounting Precision Optics into Optical Assemblies

Any number of optical elements can be aggregated into an optical system. An optical assembly may be removed from one optical system and used elsewhere; for example, the eyepiece of an astronomical telescope might be moved to a different telescope. To combine precision optical elements into assemblies, multiple elements need to be joined together, either directly, as in a cemented doublet lens (e.g., the one shown in Figure 3-2), or via a mechanical mount, such as a lens tube.

Adhesives, cements, and *bonding materials* are liquids used to join materials permanently. Each adhesive or bond requires a particular curing process to turn it from a liquid to a solid and remove any residual gasses. Some, such as cyanoacrylate or the common Norland adhesives, simply require time or exposure to ultraviolet light to cure. Others, including 3M's EC 2216 and EA 9394, are two-part epoxy-resin combinations that require time and/or elevated temperatures to fully cure. Some adhesives may be optically transmissive if used to join two glasses together, while others may be used to affix precision optics to their mechanical mounts.

Optical elements are precisely manufactured, so they cannot be arbitrarily assembled. Precision optical techniques exist for assembling optics into assemblies; these techniques often involve advanced metrology systems such as alignment telescopes and interferometers. Optical assemblies may require alignment to sub-micrometer, sub-microradian accuracy. Assembly alignment details are unique for each assembly, and they may be specified on an optical fabrication drawing or in a complementary alignment plan written by an optical engineer.

On ISO 10110 optical fabrication drawings, rules and drawing indicators do exist for joining materials. For multiple-element assemblies, the thickness tolerance is identified with and preceded by the capital letter **M**. The letter **A** indicates that a particular element separation is to be adjusted (for best focus or some other performance metric). The letter **V** indicates that that the distance is variable (for different configurations of the optical assembly).

LABORATORIES

Laboratory 3-A
Polarimetry of Stressed Optics

Theory

The phenomena of birefringence and photoelasticity allow the use of polarizers to investigate the mechanical and optical properties of crystalline and plastic materials. Construction of a simple polarimeter helps determine the birefringence and refractive index homogeneity distribution for these materials. It can also identify stress points that are incurred during manufacture of injection-molded plastics. This helps technicians assess the limitations of the plastics as optics, mechanical tools, and structural elements.

*Equipment **

- Linear polarizers, at least 200 by 200 mm in size (2 per group)
- Inexpensive plastic items such as magnifiers, cups, utensils, rulers, protractors, folder organizers, plastic wrap, etc. (3 items per group)
- Precision plastic optics: lenses and windows (2 items per group)
- Polished, transparent crystal or an optical-grade crystal window, made of a birefringent material such as sapphire, calcite, or quartz (1 per group)
- White-light optical source, such as a white LED light, a mercury arc lamp, or an incandescent tungsten-halogen or xenon filament (1 per group)
- Lens or mirror to diverge the source—note that source divergence might be inherent to the source's construction, such as in the reflector of a halogen flood light or the integrated lens over an LED (1 per group)
- Translucent ground glass plate diffuser, at least 200 by 200 mm in size (1 per group)

Procedure

1. On an optical bench, set up the white-light source to uniformly illuminate the translucent diffuser using the diverging lens.
2. Place one of the linear polarizers directly in front of the diffuser.
3. Place one of the plastic items to be assessed directly in front of the first polarizer.
4. Place the second, analyzing polarizer (the analyzer) after the plastic item. The polarimeter may be viewed by looking back through the two polarizers towards the diffuser. The birefringence of the plastic item should be evident via colored bands in the material. The colors, but not the distribution, of these bands will change as the analyzing polarizer is rotated.

5. Observe the color bands through the polarimeter. Take a photograph or draw a sketch in your lab notebook to show the lines of equal stress concentration—these are the bands of uniform color where the refractive index is homogeneous. Regions where colors rapidly change are stress points in the material, where the refractive index changes significantly. If the material is injection-molded plastic, a very colorful region will indicate the point of injection for the plastic.
6. By comparing colors, make rough estimates of the optical path difference (OPD) introduced by the stress birefringence between neighboring regions of the part tested. For example, if a yellow region neighbors a green region, the difference in wavelength is about 50 nm or so (590 nm minus 540 nm). How can this be used to quantify the stress-birefringence-induced OPD between these regions?
7. Repeat steps 2 through 6 for each plastic item to be investigated.
8. Address the following question in your lab notebook:
    a. Polarimetry helps structural and civil engineers determine stress points in a material. Which regions do you think are the most fragile points of the plastics investigated?
    b. Injection-molded optics may have poor refractive-index uniformity at their edges, but not within their clear apertures. Are there obvious clear apertures for the plastic optics, based solely on their homogeneity? For each optic, if regions of striae are apparent, sketch their distribution within the clear aperture of the optic.
    c. How do the stress and birefringence distributions (the homogeneity) differ between the inexpensive plastics and the precision optical materials and crystals?

* Note: An overhead projector with a screen works well as the source, lens, and diffuser. For setup, in place of steps 1 through 4, simply place one polarizer atop the projector, the items to be assessed atop the first polarizer, and the second polarizer atop the items. The projection shows the birefringence as the second polarizer (the analyzer) is rotated.

Laboratory 3-B
Under the Hood

Theory

An optical inspection hood helps technicians inspect parts for scratches, digs, coating flaws, and cleanliness. An inspection hood is simply a dark box with a uniform light inside. It can be constructed of cardboard or made by painting a plastic container, allowing only holes for the light source, the parts to be inspected, and the inspection technician's hands and eyes. The box should be blackened so that all reflections from the optic being inspected have a uniform background. The source should uniformly illuminate an area of at least 100 by 100 mm. The light emitted should be narrowband—a diffused, filtered incandescent or diffused, single-color LED source works well. Commercial inspection sources are filtered green due to the high sensitivity of the human eye.

Flat, smooth materials work best as educational parts for inspection in this experiment, but the materials do not necessarily have to be optical materials. Personal items that are considered optically clean, such as the students' sunglasses or dinner plates will be interesting to inspect, in addition to polished windows, lenses, and mirrors. This is a qualitative experiment, so students should make comparisons between common materials and optical materials. Industrial standards for scratch/dig provide a reference to which students will compare the inspected parts.

Equipment

- Materials to construct an inspection hood (1 hood per group)
- Black matte paint or black felt to coat the inside of the hood (1 per hood)
- Filtered inspection source, preferably green, at least 100 by 100 mm in size (1 per group)
- Clean, flat, smooth common materials (5 per group)
- Optical materials such as windows, lenses, mirrors, prisms, etc. (5 per group)
- Scratch/dig reference set (1 set per class to share)

Procedure

1. Construct an inspection hood from cardboard or plastic, leaving holes for hands, eyes, and a large-area source; paint it black matte or line the hood with black felt.
2. Inspect the optical items first for scratches and digs, and then observe their cleanliness. Document how you discern the permanent surface features (scratches and digs) from the nonvolatile residue (NVR) and other surface contaminants.
3. Next, inspect the common, non-optical materials for scratches and digs. Document which materials compare in quality to the optical materials, and which are much lower quality.
4. For each item inspected, estimate the size and number of surface contaminants, and the item's overall cleanliness level.

5. Finally, inspect the scratch/dig references to observe the various degrees of optical surface quality. Compare each material inspected to the appropriate reference.

Laboratory 3-C
Interferometry 101

Theory

Many types of interferometers exist, but one of the most basic and instructive for optical measurement is the so-called Michelson interferometer. This interferometer splits one collimated source into two beam paths using a beamsplitter. Flat mirrors then reflect the two beams back along the same direction from which they came. They reenter the beamsplitter and are recombined to interfere on a screen in the "fourth leg" of the interferometer. The basic setup is shown in the figure.

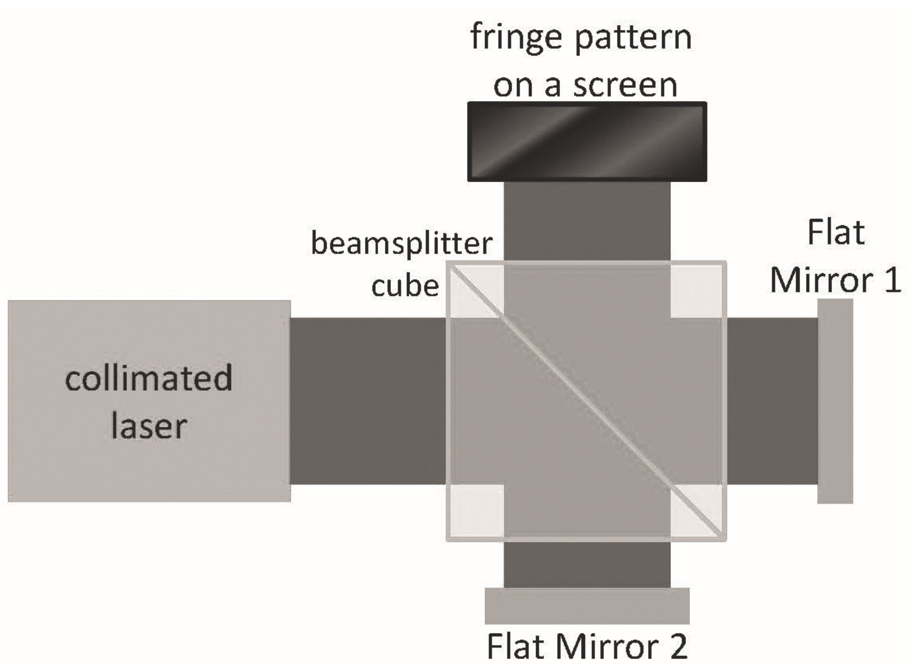


Figure 3-22 *Schematic of an Interferometer*

Equipment

- Low-power helium-neon laser (1 per group)
- 20x microscope objective and mount to diverge the laser (1 per group)
- Lens with a focal length of about +50 mm and a diameter of 50 mm, used to collimate the laser (1 per group)
- Shear plate interferometer (1 or 2 per class to share)
- Beamsplitter cube, at least 25-mm on a side (1 per group)
- Flat mirrors mounted with tip/tilt actuators (2 per group)
- White screen (1 per group)
- Thin plastic or glass material, such as a CD case cover or plastic wrap (2 pieces per group)

Procedure

1. Collimate the laser to at least a 25-mm collimated beam diameter. If the laser is collimated to a 50-mm diameter, it is acceptable to overfill the beamsplitter aperture.
2. Align this collimated beam through a cube beamsplitter. Two beams of light should be exiting the cube beamsplitter, one straight through, the other reflected through the bottom face.
3. Align Mirror 1 (flat mirror) to the straight-through beam. Place Mirror 1 about 50 mm from the cube beamsplitter output. Use the reflection back towards the laser to align both the beamsplitter input face and Mirror 1's surface so they are perpendicular to the laser.
4. There should now be a beam of light that is directed out the top face of the beamsplitter towards the "fourth leg" of the interferometer. This is the reflection off Mirror 1, back into the beamsplitter, and reflected by the beamsplitter toward its top face. Place a white screen to capture this beam of light.
5. Place Mirror 2 (flat mirror) about 50 mm from the bottom face of the beamsplitter. The beam of light mentioned in step 2 as exiting the bottom face of the beamsplitter will reflect from Mirror 2 and reenter the bottom face of the beamsplitter. The beamsplitter will direct part of this beam of light reflected from Mirror 2 through its top face. Align Mirror 2 so that the beam of light reflected off of it and passing through the top of the beamsplitter overlaps Mirror 1's reflected light on the screen.
6. Secure all optics, mounts, and the screen.
7. Begin to adjust the tip and tilt of the mirrors until fringes form on the screen. If the mirrors are indeed flat, only linear tilt fringes should form. When the mirrors are tilted to large angles, the linear fringes formed may be of such high spatial frequency that they are impossible to resolve by eye. Make careful adjustments to the mirror tilt. (It may be helpful to temporarily remove the microscope objective that is diverging the laser, and then align the thin laser beams to overlap through the interferometer.)
8. Describe the difficulties encountered when obtaining fringes. How do vibrations and air currents in the room influence you results?
9. What does it mean when only one fringe exists?
10. Place the thin plastic or glass material in front of one of the mirrors and describe how the fringes change shape and contrast.

Laboratory 3-D
Draw Something

Theory

Any object that interacts with light can be drawn to ISO 10110 standards. Take a simple, common object, such as a car windshield, a cell phone screen, or a spoon, and draw it with tolerances and ISO 10110 specifications such as surface texture and coating. Consider the importance of reference surfaces, and ensure that the surfaces important for its use receive stricter tolerances. Remember, an optical surface of a precision optic has tighter tolerances than a surface that interfaces to its mount.

Equipment

- common object (1 per person)
- caliper or ruler to measure lengths (1 per person)
- protractor to measure angles (1 per person)

Procedure

1. Locate an appropriate object that interacts with light.
2. Sketch it to scale.
3. Add appropriate ISO 10110 notes to the drawing, including the object's surface form, coatings, surface texture, etc.

PROBLEM EXERCISES AND QUESTIONS

1. List at least ten specifications *related to optical materials* that might be included on a drawing of a precision optical element.

2. List at least five specifications *related to optical surfaces* that might be included on a drawing of a precision optical element.

3. List the thirteen types of specifications indicated on an ISO 10110 optical drawing.

4. Make a sketch of a simple lens per ISO 10110 drawing specifications, listing as many specifications as possible. Use ISO 10110-11, defaults for untoleranced data, as a reference. Include as many mechanical drawing features (center lines, thickness measurements, etc.) as possible.

5. Sketch and explain the three important regions of a stress–strain curve.

6. For a 10-mm thick sample of acrylic, an OPD of 64 nm is created for light at a wavelength of 555 nm. If its photoelastic constant is $8 \cdot 10^{-6}$ cm²/N, what is the residual stress in this plastic?

7. On an ISO 10110 drawing, what does the specification **0/ 10** mean?

8. Define homogeneity and striae. Explain two methods of measuring these important optical parameters.

9. The surface figure error specification for a 50-mm mirror is 35 nm RMS, 160 nm PV. What is its equivalent RWFE specification?

10. Explain the difference between surface figure error, TWFE, and RWFE.

11. On an ISO 10110 drawing, what does the specification **3/ 12(10/–) RMSi < 2, measured at 632.8 nm** mean? What is the significance of the 632.8 nm part of the specification?

12. During a Knoop hardness test, a load of L = 518.6 kg_f was applied to an optical material, causing an impression area with its longest dimension measuring d = 3.0 mm. This material's hardness is determined to have a value of HK = 820 kg_f/mm^2. What value is used for the correction constant, C, during this test? This value is considered the ideal correction factor for a perfectly shaped pyramidal diamond indenter point.

13. A scratch is measured to be 3.5 µm in diameter. Is a 10-µm diameter rouge particle or a 0.35-µm-diameter rouge particle more likely to be responsible?

14. How would a surface's coating be specified if it was high-reflectivity (HR) for all visible light?

15. If a drawing of a 25-mm-diameter lens has "Indications according to ISO 10110" written on it and there are no specifications for bubbles and inclusions, inhomogeneity and striae, surface form, or surface imperfections, what tolerances may be assumed during manufacture of this lens?

Advanced Problem Exercises and Questions

16. Research the photoelastic constants for five different plastic and five different glass optical materials. Explain why different materials have different photoelastic constants.

17. Some asphere designs require higher-order terms to improve optical performance. This can lead to a significantly different final shape for the surface with only slight changes to the surface sag equation. A convex paraboloidal optical surface has a 100-mm diameter and a 200-mm radius. What material thickness needs to be removed at its edge to make the same paraboloidal shape that adds the terms $a_4 = 5.0 \cdot 10^{-9}$ /mm^4 and $a_6 = 6.0 \cdot 10^{-12}$ /mm^6?

18. Errors are statistical quantities called variances, so they sum in quadrature. For example, the wavefront error imposed on a beam of light that reflects from five sequential surfaces would combine as follows:

$$total\ wavefront\ error = \sqrt{RWFE_{surface\ 1}{}^2 + RWFE_{surface\ 2}{}^2 + RWFE_{surface\ 3}{}^2 + RWFE_{surface\ 4}{}^2 + RWFE_{surface\ 5}{}^2}$$

A three-mirror telescope is specified to have a total RWFE of less than 100 nm RMS. Write the specification for each of the three individual mirrors, given that the primary mirror is allowed to contribute 50% of the total RWFE, and the remaining 50% is split between the secondary and the tertiary mirrors.

19. An optical surface's form is specified to be **3/ 2(5/–)**. The surface is measured using an interferometer with a helium-neon laser at 632.8 nm. You measure 4.4 fringes of peak-to-valley error across the part. Why is or is not this part acceptable?

20. The surface quality (imperfection) specification for the right lens surface of Figure 3-1 is

5/ 5x0.10; C5x0.20; L2x0.01; E0.50

After fabrication, the blemishes shown in Figure 3-23 were found on the substrate surface of serial number 3A. The dotted line shows the clear aperture, and the values indicated are the largest dimensions of the imperfections circled. The values attached to the scratches indicate their widths.

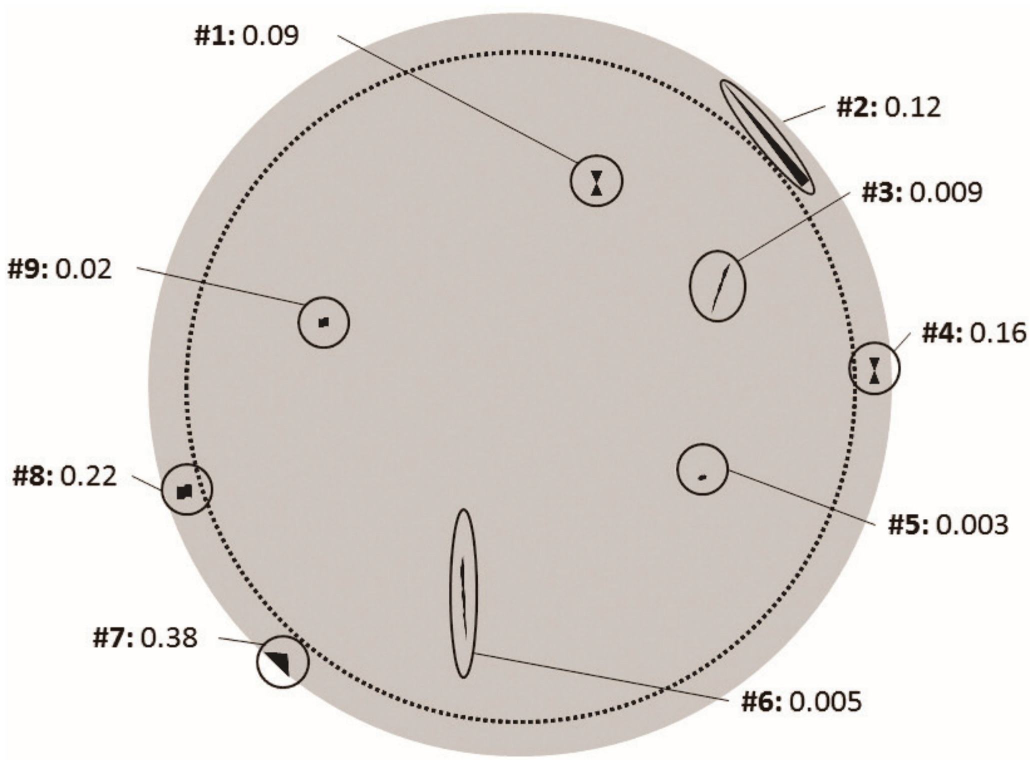


Figure 3-23 *Blemishes found on Substrate Surface Serial #3A*

Why does or does not this part meet its specification?

21. How would an optical window's surface coating be specified if it was supposed to block light from the primary and secondary harmonic wavelengths of a common Nd:YAG laser (in the in-band region), but transmit at least 30% of all other VIS and NIR wavelengths (the out-of-band region)? The in-band blocking should be to at least OD 4. Allowed transition region is ± 30-nm between in-band and out-of-band; spectral slope should be approximately 1% per nm or steeper. Draw a plot of the important points on the spectral transmissivity curve, T(λ).

22. The following specifications are listed on an optical drawing. Which three specifications conflict and require further clarification before fabrication?

    R 100 ± 2 CX

    chamfer: 0.2 – 0.4

    λ **AR 405 – 495, 600 – 750**

    λ **HR 515, 532, 632.8, 850**

    3/ 50(2/-)

    4/ 10'

    5/ 5x0.2; C5x0.2; L10x0.1; E0.35

23. A cleanroom particle counter measures 93,494 particles that are between 0.1 and 0.2 micrometers in size, 393 particles that are between 0.3 and 0.5 micrometers in size, and 292 particles that are larger than 1.0 micrometers. What class is this cleanroom?

24. The laser-damage threshold for a surface is given as **6/ 100; 632.8 nm; 5**. If only a 10-milliwatt helium-neon laser is available, what focused spot diameter is required to perform these laser-damage tests? What focal length lens is required if the beam diameter is 5 mm?

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GLOSSARY

- *Abbe number* defines the dispersion of a transmissive optical material, typically at three wavelengths within the transmission spectrum of the material
- *Absorption* is the conversion of light to another form of energy, such as heat, sound, or radiation.
- *Absorptivity* is the general spectral property that describes how a material absorbs light at each wavelength.
- *Absorptance* is the specific property of how a particular material sample absorbs light. For example, you can state, "For wavelengths around 1 µm, the *absorptivity* of aluminum coatings are higher than a dielectric coating," and "At 1.064 µm, I measured the *absorptance* of aluminum-coated mirror, serial number 19, to be 500 ppm, which was 300 times the *absorptance* of the dielectric-coated mirror, serial number 11."
- *Aberrations* are deformations to a wavefront of light that occur when the light interacts with an optical surface. Any aberrations are deviations from an ideal wavefront.
- *Absolute* measurements are made without a reference, and not dependent on anything else.
- *Accuracy* is the closeness of a measured value to a desired, nominal value.
- *Adhesive and bonding materials* are liquids that are used to join two materials together permanently. Some adhesives may be optically transmissive to join two glasses together, others may be used to join precision optics to their mechanical mounts.
- *Afocal* telescopes have collimated input and output, imaging an object at positive infinity to an image at negative infinity.
- *Albedo* is a ratio of the total light scattered to the total light incident on a material.
- *Amorphous materials* have their atoms or molecules arranged in a random manner, without structure.
- *Analyzer* (or *analyzing polarizer*) is a polarizer that is located after light of a known polarization interacts with an optical material. Its purpose is to analyze the changes in the polarization state relative to the known polarization prior to the interaction with the optical material.
- *Aspheres* are departures from spherical surfaces that are mathematically created by taking a conic section, whereby a cone is cut, and the resulting cross section is revolved around its axis to form a particular three-dimensional surface. Four different types of shapes can be formed, including a sphere, an ellipsoid, a paraboloid and a hyperboloid. Shaping optical surfaces with aspheres can improve the image quality of an optical system.
- *Attenuation* is the process of diminishing the power of an optical signal, typically due to absorption.
- *Autocollimating alignment telescope* (or *autocollimator*) is a telescope with a narrow field of view used to perform precision optical alignments and angle measurements.

- *Average* or *mean* is the typical, expected value of a data set or measurement. Arithmetically, it equals the sum of all measurements divided by the number of measurements.
- *Bevels* (see *chamfers*)
- *Bi-directional reflectance distribution function (BRDF)* represents the amount of light that is scattered to all angles backward, into the hemisphere towards the source
- *Bi-directional transmittance distribution function (BTDF)* represents the amount of light that is scattered to all angles forward, into the hemisphere away from the source
- *Birefringence* is the phenomenon that occurs because some optical materials have a refractive index that depends on the direction light interacts with the material. It is common for crystalline and plastic optics.
- *Blanks* are precision optical substrates that have not yet undergone any precision optical machining.
- *Bolometers* are resistors that change their resistance value with temperature.
- *Brittleness* is a material property associated with easy fracture under stress without significant strain (deformation).
- *Bubbles* are trapped pockets of air within the bulk structure of a glass optical element.
- *Calibration* describes the process of comparing measurements made by a system or tool to a known, accurate standard, and then applying the appropriate correction values to ensure that future measurements are made relative to the standard.
- *Calipers* are hand tools used to measure distance or length.
- *Calorimetry* is the measurement of temperature, usually associated with precision absorption measurements.
- *Center thickness* is the thickness along the physical center of an optical element; it is not necessarily along the optical axis of the element.
- *Centration* is the process of ensuring that the physical center of an on-axis optical element coincides with its optical axis, spacing all edges equally from the optic's vertex.
- *Chamfers* or *bevels* are features cut into the edges of precision optics to make them less sharp and safer to handle. They are typically cut at 45° to the optical surface so that they form a thin, flat edge around the optic. The size of a chamfer or bevel is typically measured from the edge of the optic inward, not along the length of the chamfer face.
- *Chemical vapor deposition* (CVD) involves the formation of a bulk ceramic structure by causing a chemical reaction between atoms or molecules to take place within a vacuum chamber, and then allowing the resulting compound to deposit down onto a substrate until a solid material forms.
- *Cleanliness classes* define the standards for how clean a *cleanroom* must be when working with precision optics.
- *Cleanliness levels* define the standards for how clean an optical surface must be.

- *Cleanrooms* are special rooms from which air particles are removed continuously by creating a positive pressure from ceiling to floor with respect to the outside world, effectively blowing contaminating particles outside at all times. Cleanrooms are required for handling, cleaning, coating, and assessment of precision optics. Small workbench areas that are clean may be called *clean hoods* or *flowbenches.*
- *Cleanroom supplies* include all equipment required to work in a cleanroom without introducing external contaminants and particles that come off the human body. (To contrast with personal protective equipment that is intended to keep the human body safe from the cleanroom laboratory chemicals.) Equipment including cleanroom suits (aka "bunny suits"), smocks, finger cots, gloves, masks, hair nets, beard covers, and shoe booties are all cleanroom supplies.
- *Clear aperture* or *effective diameter*, denoted $\varnothing_e$ per the ISO 10110 optical drawing standard, is the region of the optical surface that interacts with light. It is always smaller in extent than the physical diameter or surface area of the part.
- *Cleavage* is a property that describes how crystals can be sheared apart along their crystal planes.
- *Coefficient of thermal expansion (CTE)* describes how a material changes size with temperature.
- *Collimated light* travels in a straight line, neither diverging nor converging.
- *Computer numeric control (CNC) milling machines* are advanced multiple-axis (usually three or five) cutting machines that take raw, three-dimensional mechanical drawing files from the optical or optomechanical designer, and use a computer program to control a cutting tool that shapes a raw optical blank into its *near-net shape* prior to optical finishing.
- *Conic constants* mathematically represent aspherical surfaces' departure from a sphere. Conic constants, k, for aspheric optical surfaces are as follows,
  $k < -1$ are for hyperboloids, $k = -1$ for paraboloids, $-1 < k < 0$ for ellipsoids rotated about their major axis, $k = 0$ for spheres, and $k > 0$ for ellipsoids rotated about their minor axis.
- *Coordinate-measuring machines (CMMs)* are used to measure precisely the features of a mechanical part or precision optic using an encoded multiple-axis (usually three or more) stage and a calibrated sapphire (or ruby) ball tip. The stage is made of a large frame of precision rails within which the CMM can measure the dimensions of parts. The sapphire tip contacts the part being measured from multiple directions, and the points of contact are used to map the dimensions of part's surface.
- *Coring machines* are used to cut the central portion out of a precision optical blank to create annular optics. They operate in a manner similar to *lathes*.
- *Crystal* materials are made of atoms or molecules that are arranged in an ordered manner. Materials can be caused to *crystallize* by forming them slowly and deliberately, particularly by using a host layer to start the crystallization process. *Monocrystalline* materials consist of one uniform crystalline pattern throughout the bulk of the material, while *polycrystalline* materials are comprised of multiple monocrystalline regions with different orientations throughout the bulk, separated by *grain boundaries*.

- *Curvature* of an optical surface is the reciprocal of its radius of curvature. It has units of one over length.
- *Degreasers* are used to remove chemicals, such as greases, oils, paints, waxes, temporary epoxies, and pitches that are introduced during fabrication processes for handling and protection prior to final optical finishing and coating.
- *Detectors* generally describe a material, component, or system that senses light and converts it to an electrical signal.
- *Diameter, outer* describes the maximum physical extent of a circular part.
- *Diameter, inner* describes the maximum extent of the distance cored out of an annular part.
- *Diffraction limit* is the theoretical optimum performance limit for an optical system. If an optical system is said to be diffraction limited, its optics can no longer be improved in fabrication or alignment.
- *Diffraction* is the separation of light into its spectrum by transmission through or reflection off a structured surface.
- *Diffraction efficiency* is the ratio of the power of light diffracted into an order relative to the power of the incident light. The diffraction efficiency of a grating is controlled by the profile and shape of its grooves.
- *Digs* are pits within an optical surface or coating. They, along with scratches, describe the optical surface quality.
- *Discoloration* is a uniform non-clear color throughout the bulk of a material, due to uniform absorption of particular wavelengths throughout the entire material.
- *Dispersion* is the phenomenon that occurs because refractive index is a spectral quantity. Like diffraction, it may be used to separate an optical source into its spectrum.
- *Distance-measuring interferometers (DMIs)* are interferometers with lasers that are pointed by a two-axis gimbal system. DMIs operate by counting interferometric *fringes* to determine the distance from the tracker to the target. The beam is returned to the DMI using precision retroreflectors.
- *Dopants* are impurities that are deliberately added to a material to alter its optical, electrical, or mechanical properties.
- *Ductility* is a material property associated with high elastic deformation under stress.
- *Durability* is an optical material or coating's ability to preserve its surface quality by resisting environmental conditions such as abrasion, adhesion, humidity, fog, or salt water.
- *Edge radii* are rounded features cut into the edges of a precision optic to make it less sharp and safer to handle. They are specified as a radial distance, measured from the edge of the optic inward.
- *Edge thickness* is the thickness of a precision optic at its outer edge. This thickness should be large enough to safely handle the optic. A machine that applies edges to a precision optical element may be called a *edging machine.*

- *Elastic deformation* occurs when stress is applied to and removed from a material, and it returns to its original shape.
- *Ellipsometry* is a polarization-based measurement technique used to determine the complex refractive index of an optical material, particularly thin films. *Ellipsometers* are instruments used to perform ellipsometry measurements.
- *Etchers/engravers/markers* are used to add text to the edges of precision optics to name and number the parts. Marks may be as simple as a felt-tipped marker, but are usually permanent features applied by acid etch or laser engraving.
- *Evaporation* is a thin-film coating technique by which a substrate is coated when the material to be deposited (the *evaporant*) is boiled thermally, as on a stove, or by using a high-energy beam of charged particles like electrons or ions. This method creates a gas of the evaporant that accumulates as a film on the substrate surface.
- *Exceptions* are deviations from optical drawing specifications made by the vendor of an optical element, and (usually) agreed upon with the customer prior to fabrication.
- *Fluorescence* is a form of luminescence that indicates material's ability to emit low-frequency (redder) light when higher-frequency (bluer) light is incident upon it. Glow-in-the-dark materials are common fluorescent materials.
- The *f-number* of an optical system is simply the ratio of its focal length to its clear aperture.
- *Focal length* is the distance from the principal plane of an optical system to the focal point.
- *Focal point* is the point at which light from optical infinity converges.
- *Fourier-transform infrared (FTIR) spectrometer* is an optical instrument used typically to measure the infrared radiometric properties (reflectivity or transmissivity) of a material.
- *Fracture toughness* is most specifically related to digs, a material's ability to resist cracks, chips, and other forms of fracture.
- *Fractures* are physical breaks in a material's structure.
- *Freeform* surfaces are surfaces of any form that can be freely described, usually by a complex mathematical equation.
- *Fringes* are formed when two beams interfere in an interferometer. They represent the relative phase of one beam relative to the other as dark and light bands.
- *Gauge blocks of thickness and angle* are calibrated references (of thickness or angle) that are used as references for distance and angle measurements. Thickness gauge blocks may also be called *parallels.*
- *Gauge of height, hole, and depth* are tools used to measure the size of a precision optic's features. They are either calibrated tools or measurements are made relative to a reference such as a granite slab.
- *Glass code* is a six-digit glass code concatenates the first three decimals of the refractive index with the first three significant figures of the Abbe number, both as measured at the helium d-line of 587.56 nm. For instance, if the refractive index of a material is 1.ABC and its Abbe number is XY.Z, the glass code is ABCXYZ.

- *Gloves and finger cots* are protective equipment designed to keep human contaminants off optical surfaces and to keep potentially hazardous cleanroom chemicals off the user. Either is required when handling precision optics. Gloves cover the entire hand up to the wrist, while finger cots are rolled over each finger individually. They are typically made of latex or nitrile.
- *Goniometers* are two- or three-axis rotation stages designed to rotate about a point on the optical surface of a part.
- *Grain boundaries* are the regions between two monocrystalline regions within a polycrystalline material. If they are present in optical materials, they act as scattering sites.
- *Granite slab workbenches* are flat reference surfaces used for gauge-based height and depth measurements. They are often used to measure optical surfaces because they hold their extremely flat form over temperature and time.
- *Grinders* are coarse cutting materials used to shape a precision optic after it has been cut to near-net shape, prior to polishing. The material-removal mechanisms are often similar to, but coarser than those used in polishing systems.
- *Handling materials* are any items that come in contact with precision optics throughout their fabrication process. Handling materials should always be cleaner than the precision optic at each stage of the process. Materials for handling finished, coated optics must be cleaner than the specified requirement for the optic itself.
- *Hardness* is a material's ability to withstand pressure (force per area) without changing form.
- *Inclusions* are defects to the crystal matrix that forms the optic, usually caused by grain boundaries or impurities.
- *Impurities* are undesirable materials that happen to enter an optical material during its manufacture.
- *Inspection hoods* are dark enclosures that are used to inspect the surface quality and coating quality of a precision optic. They are made typically from a blackened box and a single large-area, uniform, narrowband (usually green) illumination source to facilitate the inspection.
- *Integrating spheres* are optical instruments used to illuminate uniformly the input plane of an optical system. These devices create the most uniform possible light source.
- An *interference pattern* (or *interferogram*) is the distribution of interferometric fringes over a detector. They are indicative of the optical aberrations or the wavefront error of an optical system.
- *Interferometry* is the science of causing two (or more) beams of light to superpose and create fringes based on the relationship of the phases of the beams of light. An *interferometer* is an essential measurement tool for evaluation and quality assurance of optical materials.
- *Internal stress* is residual force per area within the bulk of a material. Stresses are often relieved by fabrication processes such as annealing.
- *Laser trackers* measure the point locations of retroreflector targets in a three-dimensional volume. A laser from a distance-measuring interferometer (DMI) is pointed by a two-axis

gimbal system. The DMI counts fringes to determine the distance from the tracker to the targets as well as the azimuth and elevation angles of the tracker head via high-resolution angle encoders. Laser trackers are often referred to as optical or frameless coordinate-measurement machines (CMMs).

- *Lathes* are machining tools that rotate the part as it contacts a sharp tip. They may be used for cutting, grinding, or edging precision optics, among many other machining operations.
- *Linear polarizers* are optical devices that output linear polarized light when light transmits through them. They often function by absorbing light of one linear polarization while transmitting the other.
- *Loupes* (or Jewelers' loupes) are magnifying lenses with short working distances giving magnification values nominally ranging from 3x to 100x.
- *Luminescence* is a material's ability to emit light due to an external stimulus, such as an electrical signal or ultraviolet radiation.
- *Micrometers* are hand tools used to measure the thickness of a material.
- *Microscopes* are instruments used to magnify and view tiny objects. When working with precision optics, they are often used to view internal and surface flaws.
- *Mid-spatial frequency (MSF) error* is the value of an MTF curve in the middle, for spatial frequencies of moderate value. It is important because some residual material characteristics caused by optical fabrication techniques can suppress the spatial resolution of optical systems for these moderate spatial frequencies.
- *Mills* are machines used to make precision cuts in bulk materials. Unless operated by computer (see *CNC mills*), they are controlled by hand using calibrated stages and dials. They typically use a hardened steel or diamond-tipped tool to cut metal or glass to shape. *Water-jet milling* is also common for cutting optical substrates. *Bridgeport mills* are often used to refer to milling machines with their tool's rotation axis oriented vertically, with a translation stage for the part beneath it (like a drill press).
- *Modulation transfer function (MTF)* represents an optical system's ability to resolve spatial frequencies in the images it forms.
- *Monochromator* is an optical instrument that outputs narrow spectral bands of light by spatially filtering a broadband source. It is used to send individual colors onto a material during a radiometric measurement.
- *Mounting materials* are required to hold precision optical elements during grinding and polishing. These materials may include plaster, pitch, or wax, among other temporary bonding materials.
- *Near-net shape* or *raw machined blank* describes the state of a precision optic after it has been cut from a large blank piece of raw material, prior to final finishing (by grinding and polishing).
- *Nominal specifications* are the values written on a manufacturing drawing about which a tolerance will be specified. The closeness of a measured value to the nominal value gives its accuracy.

- *Non-volatile residue (NVR)* is material that remains on a surface and cannot be removed by thermal techniques such as evaporation. Often, a large amount of NVR can be cleaned, but there will always be some NVR lingering on an optical surface—this defines the cleanliness level of an optical surface.
- *Numerical aperture* of an optical system is defined as the reciprocal of twice its f-number. For an optical fiber, it equals the cosine of the critical angle times the refractive index of the fiber core.
- *Optical density* refers to the absorbance of an optical material as a base-ten logarithmic ratio of the incident to transmitted irradiance. The optical density of a material therefore is given as integers that represent the transmission of a material as factors of ten: a material with an optical density of 5 transmits ten times less light per wavelength than a material with an optical density of 4, which transmits ten times less light per wavelength than a material with an optical density of 3, etc.
- *Optical flat* describes the concept of a surface being so flat that it may be used as a reference for flatness measurements. Typically, optical flats are specified to have peak-to-valley reflected wavefront error on the order of tens of nanometers.
- *Optical infinity* describes the concept of an object being significantly distant from the optical system so that additional distance will not alter the imaging performance of the optical system. For most optical systems, an object distance of tens of meters approximates optical infinity.
- *Optical surface* describes the surface of a material that is designed to interact with light.
- *Parallels* (see *Gauge blocks of thickness and angle*)
- *Peak-to-valley* describes a measured parameter's maximum (peak) plus minimum (valley) excursion.
- *Personal protective equipment (PPE)* is any clothing worn to protect the user from the chemicals with which they work (to contrast with the equipment that protects optical hardware from human contaminants). PPE may include goggles, gloves, smocks, aprons, face masks, and booties.
- *Photoelastic effect* is a technique by which stress birefringence is observed in stressed materials by placing them into a polariscope, between two crossed polarizers, to reveal colors that represent their internal stress distribution.
- *Pitch* or *polyurethane pads* are viscoelastic (dense, springy) materials that are shaped to the desired form of the precision optic. An abrasive slurry is located between the optical material being processed and the pitch or pad, and the pitch or pad is moved over the optic (or *vice versa*) to polish the optical material into its desired shape.
- *Plastic deformation* occurs when stress is applied to and removed from a material, and it distorts and does not return to its original shape.
- *Polarimetry* is the science of measuring the polarization of light; p*olarimeters* or *polariscopes* are systems that measures light's polarization as it transmits through an optical material.

- *Polarization-dependent quantities* state that a particular property of an optical material changes with the polarization of the light that interacts with it.
- *Polishing* involves moving fine abrasives over the optical surface in a careful, repeatable manner to form the surface into the exact shape that was prescribed by an optical designer. The process of polishing is often called *finishing*.
- *Polishers* are machines used to polish optical surfaces. They are usually comprised of a rotating wheel made of pitch or a viscoelastic pad that is coated with a layer of abrasive slurry. *Planetary polishers* are polishers that have two nested stages of rotation. They consist of a large pitch or pad wheel that rotates beneath the circular optic. In turn, this circular optic rotates on its own within a ring that encloses it—this ring has a diameter of about half that of the large wheel. The result is a more uniform polish over time.
- *Porosity* is a surface defect where voids or holes remain in an optical surface, usually after coating.
- *Precision* is the deviation of many measurements from the average value measured. It is the spread about the value of the accuracy and the ability of a measurement to be reproduced consistently. A high-precision part will have a small spread about the mean measurement.
- *Principal plane* is the plane of effective refraction. For thin lenses, this is the center plane through the lens. For thick, compound lenses, it can be found by inputting collimated light, and tracing back the focused light in output space to where it meets the height of the collimated light.
- *Protective materials* are any items that are used to protect precision optics from contamination, tooling, and handling throughout their fabrication process. The protective materials should always be removable using a solvent or degreaser system. Materials used for protecting optics must might include plaster, pitch, wax, or paint.
- *Quantitative* measurements reveal a specific number, rather than a quality, about the value of a material property.
- *Radiometric properties* of a material relate how it transmits, reflects, absorbs, or emits light.
- *Radius of curvature* equals the distance from a spherical surface to its center point.
- *Radius slide* is a linear rail tool used with an interferometer to measure the radius of a surface or focal length of a lens or mirror.
- *References* are calibrated materials that may be flat, concave spherical, or convex spherical surfaces. They may be reflective or transmissive. In general, references are fabricated to standards that are at least ten times better than the surfaces to which they will be compared.
- *Reflection* is the process of light bouncing off a material.
- *Reflectivity* is the general spectral property that describes how a material reflects light at each wavelength.
- *Reflectance* is the specific property of how a particular material sample reflects light. For example, you can state, "For wavelengths less than 580 nm, the reflectivity of a gold-coated mirror is much lower than a silver-coated mirror," and "At 500 nm, I measured the

reflectance of gold-coated mirror serial number 9, to be 30% less than silver-coated mirror serial number 5."

- *Reflected wavefront error (RWFE)* is the deviation from an ideal wavefront after light reflects from a precision mirror.
- *Refraction* is the process of light bending as it moves from one optical material to another due to the difference in refractive index.
- *Refractive index* is the factor by which the speed of light is reduced in a material.
- *Refractometers* are instruments used to measure refractive indexes.
- *Relative* measurements are those made when the part being measured is compared to a reference material.
- *Resolution* is the minimum observable increment of a measurement.
- *Resolution targets* (see *Ronchi rulings*)
- *Reticles* are calibrated references that are superimposed in the image plane of optical instruments in order to calibrate the dimensions in the field of view and quantify a measurement.
- *Retroreflectors* (or *cornercubes*) are literally corners of coated glass cubes that operate by reflecting light back at the same angle of incidence in the opposite ("retro") direction. When retroreflecting, incident light bounces off all three sides of the cube before exiting the incident face traveling in the same direction. Some coating materials, such as 3M's Scotchlite (commonly seen coating street signs and running shoes), are retroreflective. Tiny spheres embedded in the coating act as an array of tiny retroreflectors.
- *Ronchi rulings* are alternating opaque and clear bands that form patterns with various spatial frequency. They are used to quantify the resolution of an optical system.
- *Root-mean square (RMS)* is a statistical measurement of the magnitude of a varying value. It is used commonly to quantify the error of an optical wavefront, since the phase of the wavefront is a varying value across the clear aperture of a precision optic.
- *Roughness* describes small, high-frequency deviations from flatness in an optical surface. Roughness indicates the material's surface finish.
- *Sag* is the departure of an optical surface from a planar surface.
- *Saws* are used to perform cuts to bulk glass, metal, and other optical materials. Common saws found in an optical shop include Miter (or "cut-off") saws as well as wire saws and band saws.
- *Scattering* occurs when light is diffusely reflected by a surface into multiple directions. Since most scattered light is no longer going in the specular direction, scattering is considered loss of energy.
- *Sclerometer* is a tool used to measure scratch resistance.
- *Scratches* are elongated cuts into an optical surface or coating. They, along with digs, describe the optical surface quality.
- *Scratch resistance* is a materials ability to withstand abrasive contact with other materials.

- *Scratch-dig references* are calibrated standards, made per the scratch-dig specifications of MIL-PRF-13830 and ISO 10110. They specify the quantity and character of the optical surface quality as a cosmetic reference.
- *Shadowgraph* is a technique used to assess the internal flaws of a material by shining diverging light through the material and casting a projection on a screen. The nature of the light's divergence will magnify flaws.
- *Shear plate interferometers* are used to test collimation. They produce straight-line fringes when a collimated beam passes through them, and curved fringes when transmitting a diverging or converging beam.
- *Single point diamond turning* (SPDT) uses a hard, sharp diamond tool embedded in a special CNC machine tool to cut a part to its final shape. This machine is a combination of a lathe and a mill—typically, they function by moving the part in a rotating chuck (mount) in three axes about a stationary diamond tip or by moving the diamond tip in three axes about the rotating part.
- *Sintering* is the process of forming a bulk material by crushing a powder of the material together under intense heat and pressure.
- *Slurries* (or abrasive slurries) are a mixture of abrasives and water that resides between the optical element being polished and the pitch that is shaped to form the optical surface; polishing gradually cuts down the optic to a smooth, high-quality surface finish.
- *Snell's Law* is the formula used to determine the angle to which light refracts when it moves from one material to another. It is dependent on the angle of incidence, angle of refraction, and the refractive indexes of the two materials.
- *Solvents* are chemicals designed to remove contaminants from the surface of a precision optical element. Common optical cleanroom solvents include isopropyl alcohol (isopropanol), methyl alcohol (methanol), acetone, and methyl ethyl ketone (MEK).
- *Sources* are any materials or systems that emit light.
- *Specifications* are values that fulfill the exact manufacturing requirements for a part.
- *Spectral attenuation coefficient* is the coefficient on the exponent of Beer-Lambert Law, given in units of inverse length. Essentially, it describes how much a material absorbs light as a function of the material's thickness.
- *Spectral quantities* state that a particular property of an optical material changes with the wavelength of the light that interacts with it.
- *Spectral signature* of a material is its characteristic reflection, transmission, absorption, or emission. This property is used to discern materials using spectroscopy.
- *Spectroscopy* (also *spectrometry*) is the measurement of the quantity of light at each wavelength before and after it interacts with an optical material.
- *Spectrophotometers* are tools used to measure radiometric properties of a material, such as reflectivity and transmissivity, in the visible portion of the spectrum.
- *Spectroradiometers* are tools used to measure radiometric properties of a material, such as reflectivity and transmissivity, in any portion of the spectrum, particularly in the infrared.

- *Specular reflection* occurs when incident light reflects from a surface in a uniform, predictable manner, as from a mirror surface. Only extremely flat or well-polished reflective surfaces reflect light in a specular manner.
- *Spherometer*s are used to measure the sag of an optical surface from a plane. Knowing the sag, the surface's radius may be calculated.
- *Sputtering* is a thin-film deposition process by which a substrate is coated when the material to be deposited (the target) is bombarded by a third material, called the *sputterant*. This method creates a fog of the coating material that accumulates as a film on the substrate surface.
- *Stereomicroscope* is a microscope with two eyepieces that provide an independent perspective of the object being viewed for both eyes, allowing a three-dimensional (stereo) image to form.
- *Storage materials* for precision optics must be cleaner than the cleanliness requirement precision optic itself. They must not contact or contaminate the optical surfaces, and they must not deteriorate over time or repeated use.
- *Strain* gives the amount of deformation of a material when a stress is applied.
- *Stray light* refers to any unexpected light in a system. It is often eliminated or controlled by baffles.
- *Stress* is an external force per cross-sectional area applied to a material.
- *Substrates* are the base material on which a coating is deposited.
- *Surface figure* is the detailed shape of an optical surface, like a topographical map with highs above and lows below the average surface shape.
- *Surface finish* gives the roughness of an optical surface.
- *Surface profilers* are instruments used to measure the roughness of an optical surface.
- *Surface quality* of an optical surface is given by the amount of scratches and digs in the surface.
- *Test plates* are references used to make relative measurements of the surface figure of precision optics.
- *Thermal shock* results in material damage when significant temperature changes are imposed on a material.
- *Tilt* refers to rotation of an optical element about a vertical axis. Generally, it includes tip in its definition, discerning as x-tilt (about a vertical axis) and y-tilt (about a horizontal axis).
- *Tip* refers to rotation of an optical element about a horizontal axis. More often, it is called y-tilt.
- *Tolerance* is the range of values allowed for a specification in order for the manufactured part to be acceptably within that specification.

- *Total indicated runout (TIR)* gives the deviation from the optical center of a precision optic. It is usually measured by placing a depth gauge at the edge of an optical element as that element is rotated about its vertex.
- *Total internal reflection (TIR)* is a phenomenon that causes complete reflection of light when it strikes a material of lower refractive index at angles greater than a critical angle.
- *Transmission* is the process of light passing through a material.
- *Transmissivity* is the general spectral property that describes how a material transmits light at each wavelength.
- *Transmittance* is the specific property of how a particular material sample transmits light. For example, you can state, "For wavelengths greater than 2.5 μm, the transmissivity of fused silica is higher than BK7," and "At 2.65 μm, I measured the transmittance of this fused silica window, serial number 2, to be three times that of BK7 window, serial number 15."
- *Transmitted wavefront error (TWFE)* is the deviation from an ideal wavefront after light transmits through a precision optical element or entire optical system.
- *Vertex* defines the center point on the surface of an optical element about which the optical element is symmetric in all directions. The radius of a spherical optical surface will pass through its center point and its vertex.
- *Wavefront* is a cross-section of a beam of light that gives the phase of the light at every point along that cross-section.
- *Waveplates* are devices that change the polarization of the light. Also called *phase retarders*.
- *Wedge* is a thickness deviation across the diameter of an optical element. Usually deliberately fabricated into optical windows.
- *Wipes or optical wipes* are soft, lint-free cloths, typically made of a synthetic material, used to package and handle precision optics.
- *Witness samples* are typically flat, 1"-diameter windows that are made of the same material, undergo similar processing, and have identical coatings as a precision optic. They are created to represent the optical properties of the precision optic while ensuring safety in handling the final (usually expensive) precision optic.
- *Wollaston prisms* are prism pairs that form basic polarimetric devices. After unpolarized incident light passes the prism pair, each polarization state is diverged to a different angle.