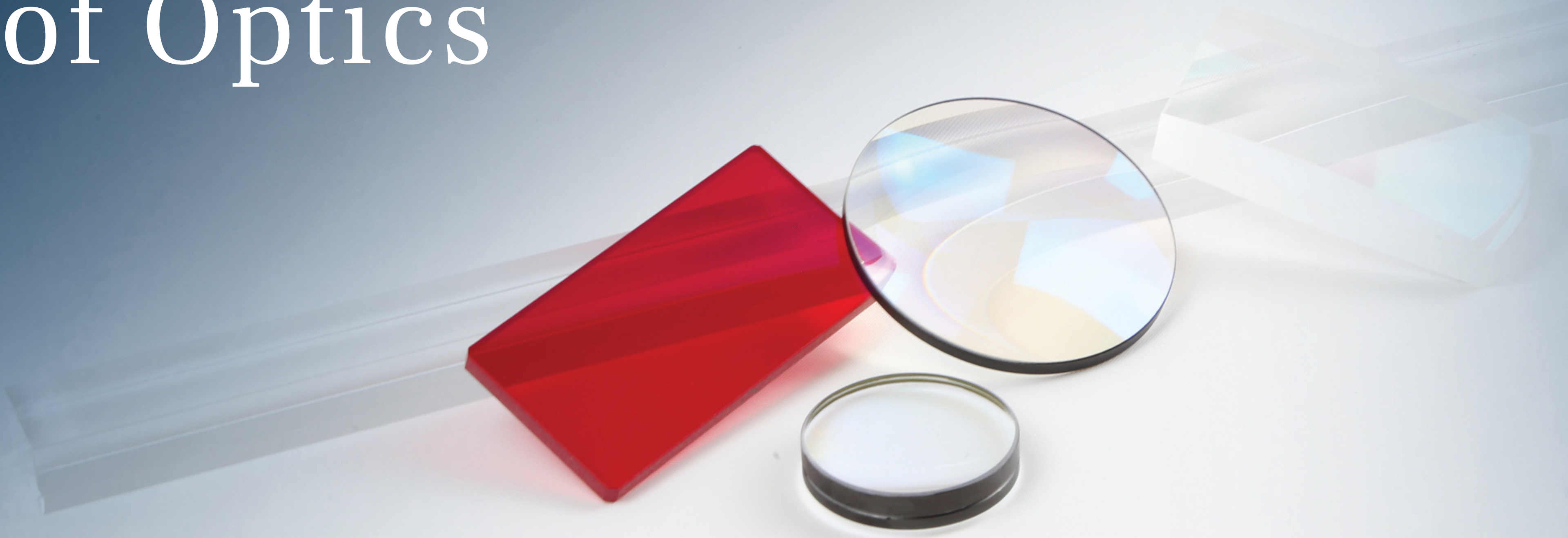
ROSS OPTICAL

A Division of Precision Optics Corporation

Fundamentals of Optics



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Introduction

Optics are an integral component of today's light-based technologies — laser systems with applications in medicine and defense, fiber optic and satellite communication, machine vision and thermal sensing, imaging and autonomous vehicles, and more. Yet, optics remain shrouded in mystery. Most people have little understanding of the mathematics that enable lenses and mirrors to work, the materials involved, or the types of problems optical designers can solve with the right lenses.

Part of this is due, of course, to the invisible nature of geometry at work; one can pick up an aspherical lens and not be able to see how or why it refracts certain wavelengths of light effectively. It may also be cultural; optics are not generally taught in the U.S. at the primary or secondary level. This means that most adults who are non-scientists lack a reliable understanding of the principles of refraction and reflection.

So, to make the design process more transparent and enjoyable, we put together this introduction to optics. We've answered many of our customers' most common questions with easy-to-understand definitions and basic illustrations. We hope this will be a useful reference, one you will want to keep at hand, refer to often, even share with others.

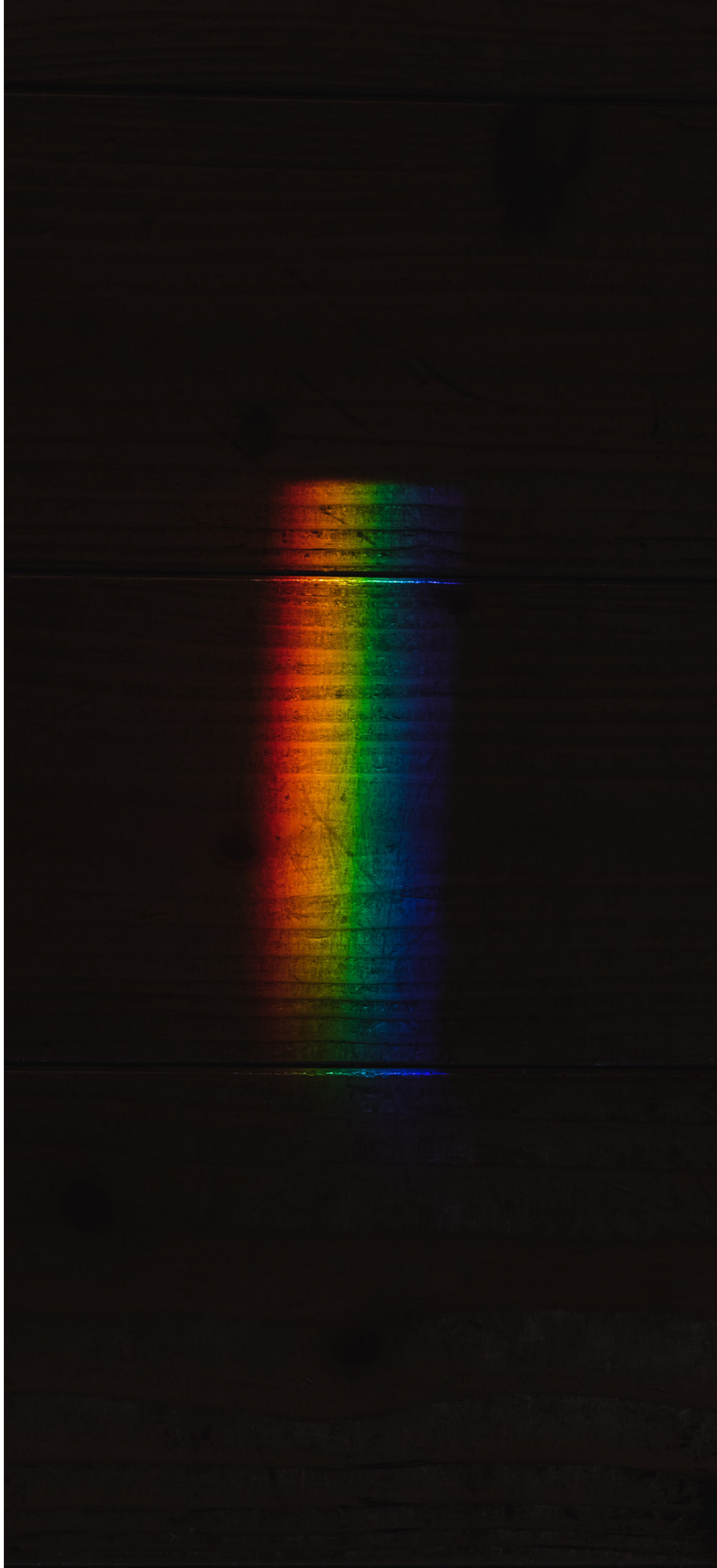
01.

Different Forms of Light

Light is both a wave and a particle. Here, we look at the properties of light as an electromagnetic wave and discuss some of light's common characteristics, including wavelength, frequency, and speed of propagation. A clear understanding of some of the ways light behaves, and how those behaviors are observed and measured, will help demystify the electromagnetic spectrum. It will also enable you to link that information to other light-based applications, such as lasers and fiber optics.

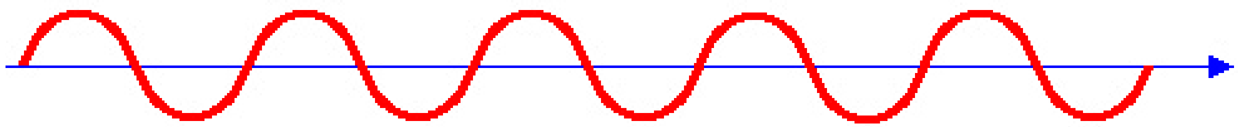
What is light?

Light is a form of radiant energy that stimulates the organs of sight. For normal human vision this relates to wavelengths ranging from about 390 nanometers to 770 nanometers and traveling at a speed of about 186,300 miles per second.



Light as a wave

Light was first recognized scientifically as a manifestation of electromagnetic energy. As such, it can be represented as a waveform, like this:



As an electromagnetic wave, light has some characteristics in common with all forms of electromagnetic energy. These include **wavelength, frequency, and speed of propagation.** These characteristics are actually related to each other, so that any one can be calculated if the other two are known.

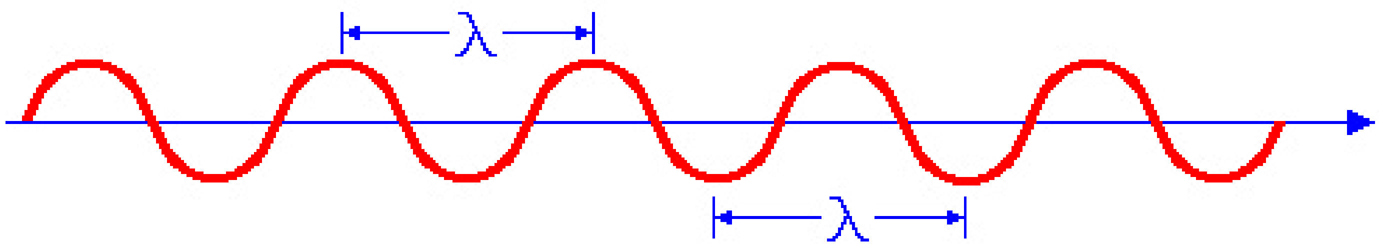
Wavelength

Wavelength is a term you will be using most often:

- What wavelength are you using for the system?
- What wavelength range do you want for this coating?
- At which wavelength do you get this focal length for this lens?

How is Wavelength (λ) Calculated?

Since light is a repeating waveform in motion, it is possible to measure the physical distance between matching points of adjacent cycles of the waveform.



> **The symbol used to represent this distance is the Greek letter "Lambda" (λ)**

Wavelength Units

This distance is normally measured in meters (m) or some decimal fraction of a meter, such as centimeters (cm). The correct units of measurement are meters per cycle (m/cycle) or some appropriate derivation.

In the case of light, the wavelength is so short that a specific distance, called the **ångstrom** (Å), has been defined.

One ångstrom = 10^{-10} m or 10^{-8} cm

The terms **you** will be hearing more often to describe wavelength are nanometers and/or microns:

One Nanometer (nm) = 10 ångstrom (Å)

For example, 550 nm = 5500 Å

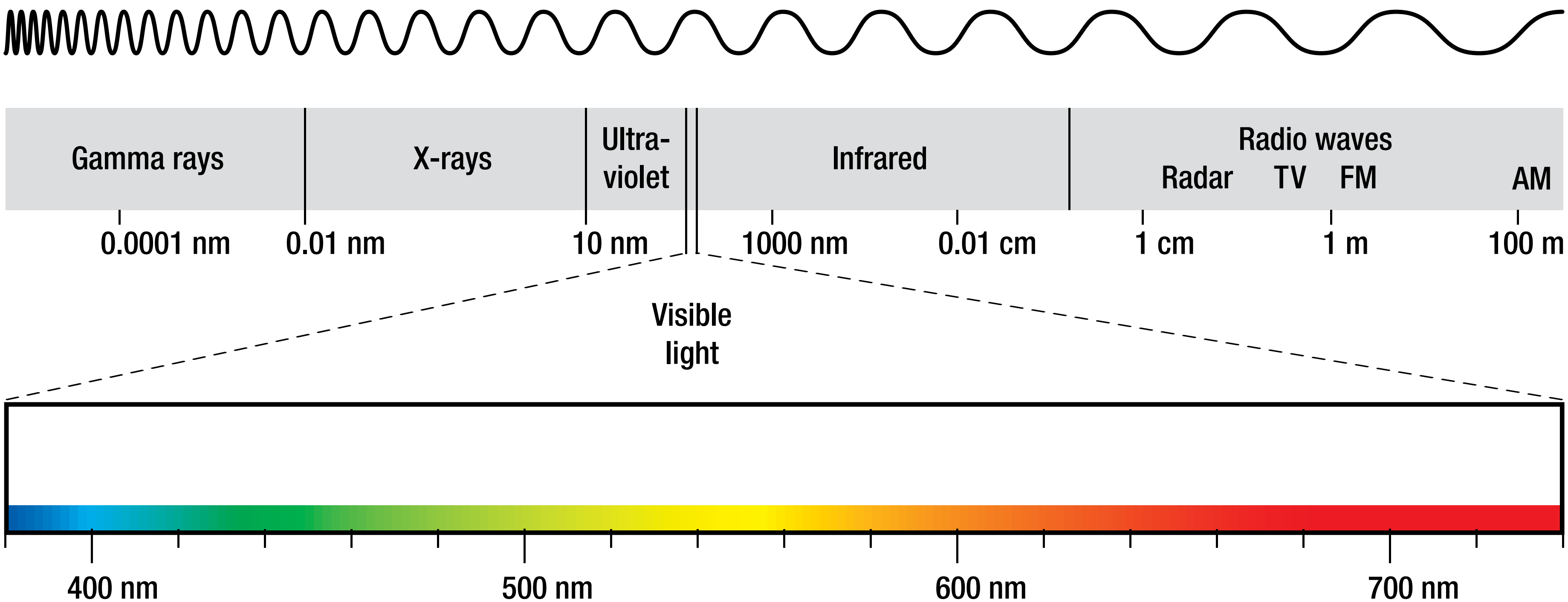
1000 Nanometers = One Micron (μ)

For example, 550 nm = 0.550 μ

Different Forms of Light

The other terms that you will be hearing are visible region, ultraviolet (UV) region, near-infrared (NIR) region and the infrared region (IR). The chart in the following page illustrates the different regions of the electromagnetic spectrum.

Visible Light Wavelengths



A Few Laser Wavelengths

Wavelength	Color	Laser Type
325	Ultraviolet	Helium Cadmium
465	Blue	Argon
488	Blue	Argon
532	Green	Diode-Pumped Solid State
633	Red	Helium-Neon
650	Red	Diode
685	Far Red	Diode
830	Infrared	Diode
1064	Infrared	Diode-Pumped Solid State
1523	Infrared	Helium-Neon

Wavelengths used in Fiber Optics Communications

850 nm | Mulitmode fiber

1310 nm | Multi and single mode fiber

1550 nm | Single mode long haul and transoceanic fiber

1625 nm | Proposed for in service monitoring

Other Wavelengths for your Interest

10^8 nm - 3 x 10^9 Hz | Microwave radio frequencies

10^9 nm - 3 x 10^8 Hz | UHF frequencies

10^{10} nm - 3 x 10^7 Hz | VHF frequencies

3 x 10^{11} nm - 1000 kHz | AM Broadcast radio frequencies

10^{14} nm - 3000 Hz | Audio frequencies

5 x 10^{15} nm - 60 Hz | Electrical power frequency

02.
Lens Design

How is a lens made? What types of things need to be understood and calculated when designing a lens? This section provides easy-to-understand definitions of five common terms that impact lens design. And, to help you visualize some of what a designer must consider, we illustrate the points and dimensions of a lens. We also explain what we mean when we refer to the “quality of a lens.”

Some Common Terms

Focal Length: There are three focal lengths commonly used. The effective focal length (f) is defined as the distance from the principal point (located inside the lens) to the focal point. The front and back focal lengths (FFL and BFL respectively) are measured from the front and rear vertex (surface) of the lens along the optical axis to the front and rear focal point respectively.

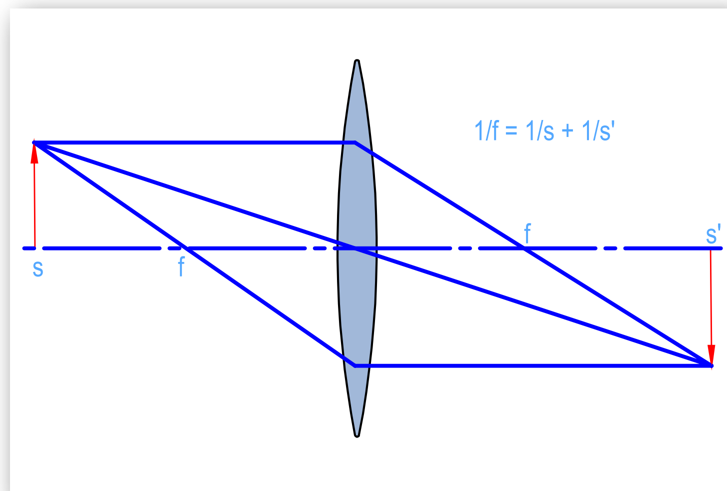
F-Number: A measure of the light-gathering power of a lens, the f-number is defined as the effective focal length of the lens (f) divided by the diameter or clear aperture of the lens.

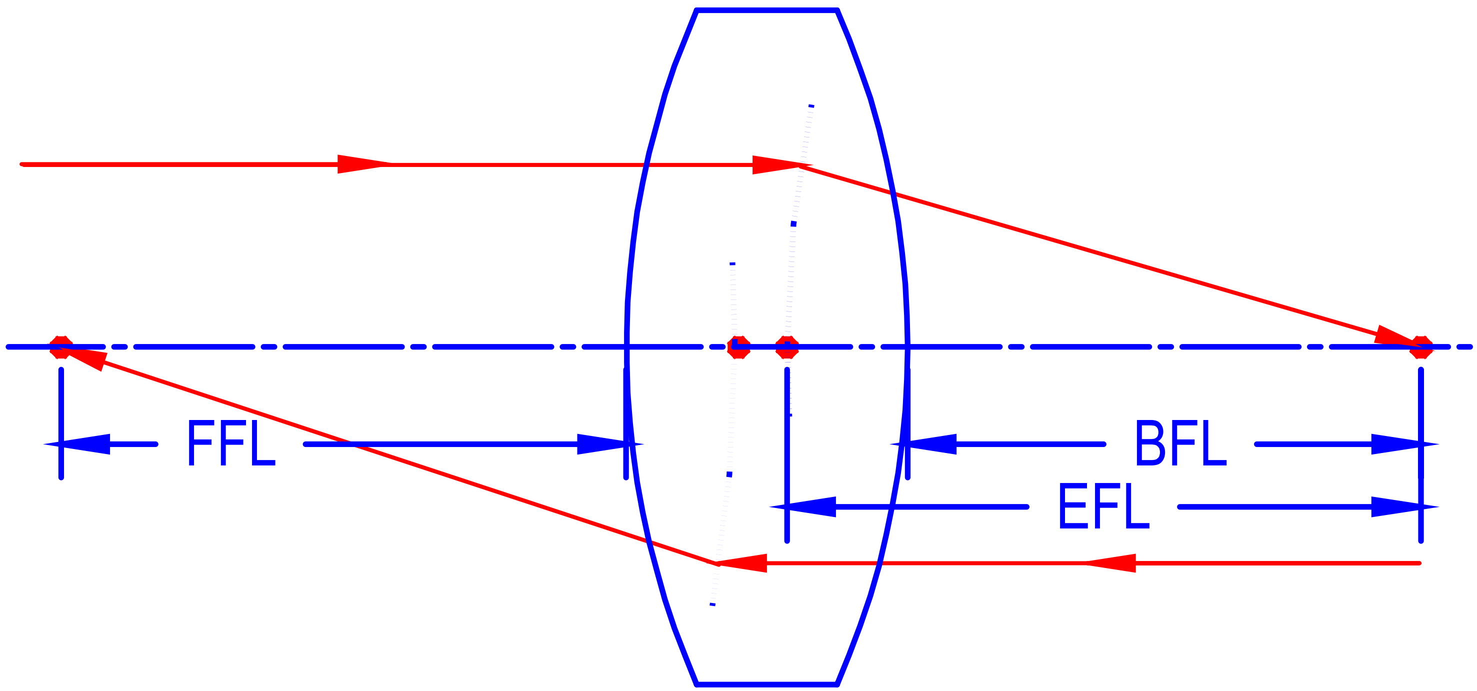
Conjugate Ratio: The ratio of the object distance to the image distance. A conjugate ratio of 1 means the object and image distances are equal. A conjugate ratio of infinity means that the incoming beam is fully collimated.

Real Image: A real image is one in which the light rays actually converge. If a screen were placed at the point of focus, an image would be formed on it.

Virtual Image: A virtual image does not represent an actual convergence of light rays. A virtual image can be viewed only by looking back through the optical system, such as in the case of a magnifying glass.

Basic Dimensions of a Lens





Basic Points of a Lens

Effective Focal Length (EFL): Distance from the Principal point to the focal point

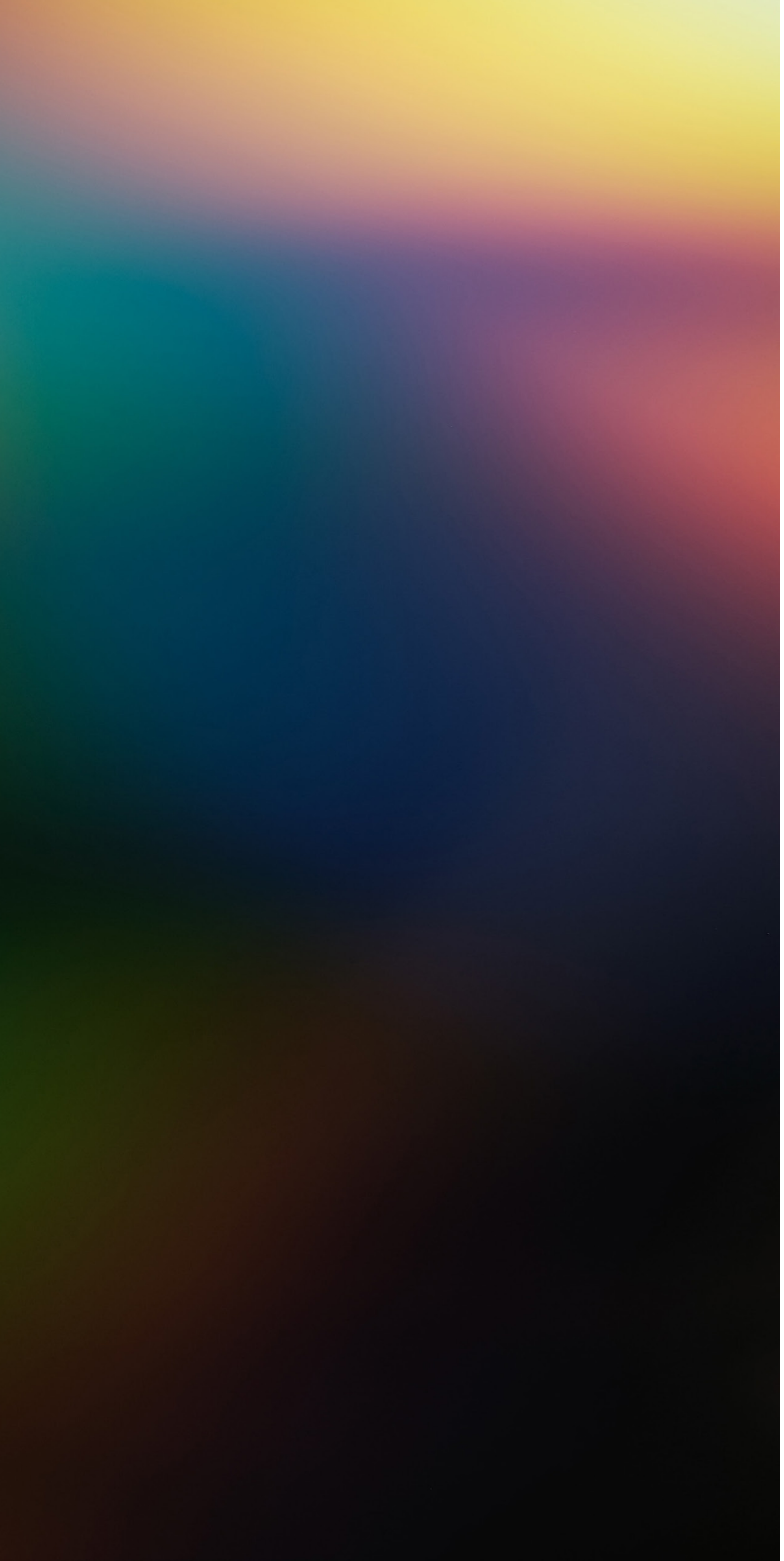
Back Focal Length (BFL): Distance from the rear surface of the lens to the focal point

Front Focal Length (FFL): Distance from the front surface of the lens to the focal point

Quality of a Lens

Surface Quality: This relates to the cosmetic features of a lens and is represented by a Scratch/Dig Specification. A standard lens is a 60/40. An 80/50 lens is commercial quality and a 40/20 lens or lower is a high quality lens.

Surface Form: This relates to how accurate the radius of the lens is and is usually represented by a power/irregularity call out. A Standard lens is 3/1, a commercial quality lens is 10/2 and a high quality lens is 2/0.5 or lower. A "perfect" lens, or diffraction limited, is typically when the surface irregularity is < 1/8 wave.



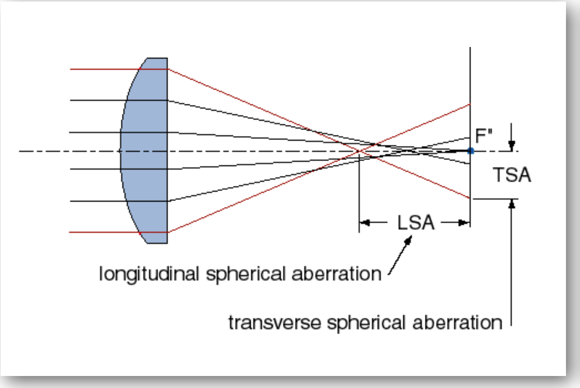
03.
Aberrations

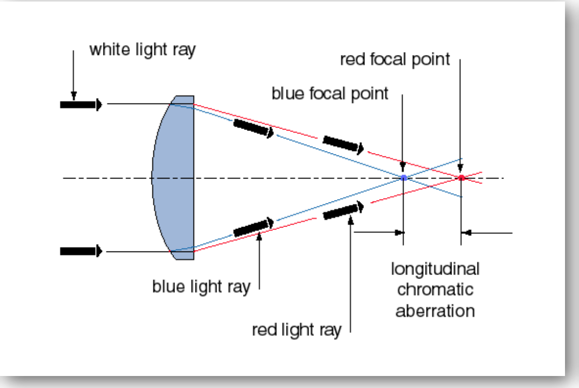
An optical aberration is a visual distortion that occurs when light — instead of being focused on a point — has spread out. Aberration is not the result of a design flaw, rather it is a normal occurrence when calculations and theories are brought into reality. In this section, five of the most common types of aberration are defined, discussed, and illustrated, along with basic suggestions to help resolve the distortion.

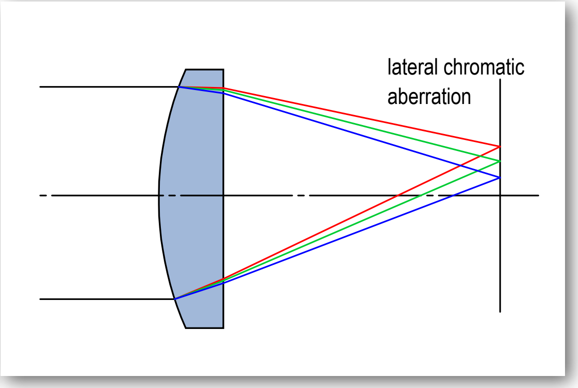
Lens Aberrations

Some of the basic optical aberration terms that you will hear:

» Spherical Aberration
» Chromatic Aberration
» Astigmatism
» Coma
» Distortion







Spherical Aberration

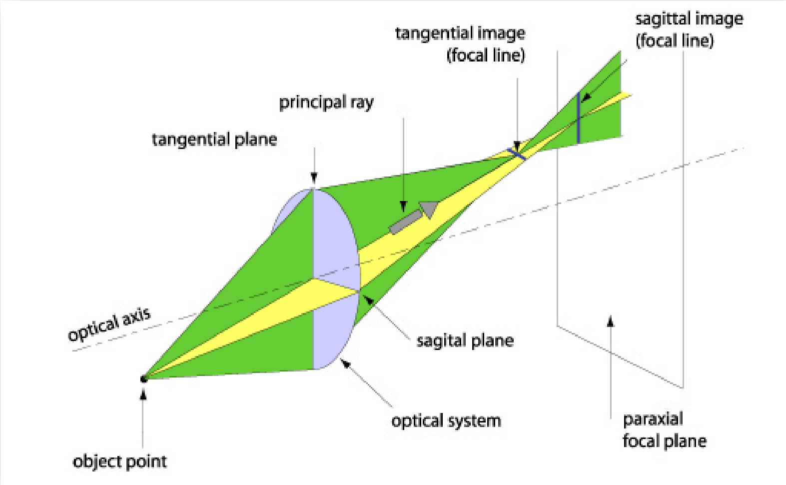
The basic aberration which leads to the failure of a lens to focus the same wavelength on the same spot. Aspheric surfaces may be applied to reduce this defect.

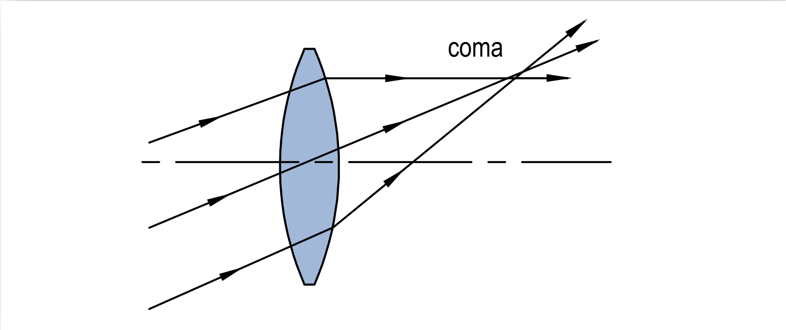
Chromatic Aberration

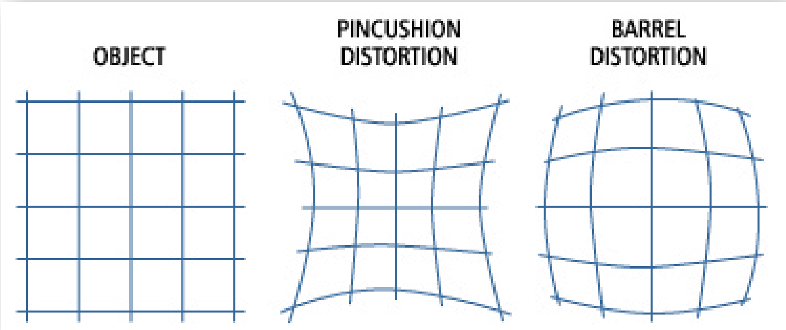
Longitudinal chromatic aberration is defined as the axial distance from the nearest to the farthest focal point. A lens has chromatic aberration when it does not focus different colors to the same spot.

Lateral Chromatic Aberration

Lateral Chromatic aberration occurs when different wavelengths are focused at different positions in the focal plane.







Astigmatism

A lens aberration that results in the tangential and sagittal image planes being separated axially. A lens that has astigmatism gives out an elliptical or circular blurred image of an object.

Coma

Coma occurs when different parts of the lens surface exhibit different degrees of magnification. This causes blurring in the image plane (surface) of off-axis object points. An off-axis object point is not a sharp image point, but it appears as a characteristic comet-like flare.

Distortion

A general term referring to the situation in which an image is not a true-to-scale reproduction of an object.

04.

Optical Materials

This section defines "optical glass" and explains important terms such as "refractive index" and "dispersion," which will enable you to understand and discuss a lens's capabilities. Ross customers will want to be familiar with the various terms we use to describe certain types of glass, such as "crown glass" and "flint glass." You may also want to familiarize yourself with the names of other optical glass manufacturers, which we have included.

Optical Materials

Optical Materials are solid substances that are either transparent in the optical part of the spectrum or in other ways useful in transforming, or redirecting light in the Ultraviolet (UV), Visible (VIS), or Infrared (IR) regions.

Optical Glass

Optical Glass is a high-quality glass material that has been specifically formulated to possess certain desirable characteristics that affect the propagation of light. Two primary parameters that define the basic nature of optical glass is its **refractive index** and **dispersion.**

Refractive Index "n" is a measure of the refractive powers of the glass relative to air which has an index of 1. The **dispersion**, expressed by the Abbe number **v**, is a measure of the dispersive powers of the glass. It defines how the glass affects light at different wavelengths. Measurement is usually done at the yellow helium line at 587 nm, which is labeled "**d**".

Glass Types

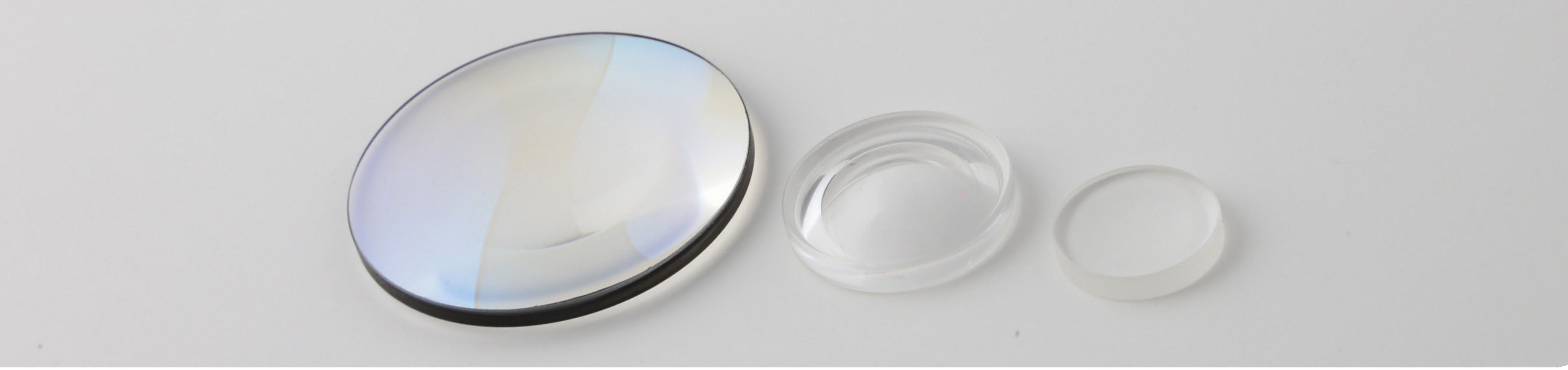
Glass Types with an $\mathbf{n_d > 1.60}$ and an $\mathbf{v_d > 50}$, as well as those with $\mathbf{n_d < 1.60}$ and $\mathbf{v_d > 55}$, are called crown glass. Examples of Crown Glasses are BK7, B270, BAK1, etc. The **K** before the number indicates crown glass.

Glass Types with $\mathbf{n_d > 1.60}$ and $\mathbf{v_d < 55}$, are called flint glass. Examples are F2, SF2, SF5, etc. The **F** in front of the number indicates a flint glass. Please note that different glass manufacturers use different glass name terminology. The terminology used above is typical of **Schott Glass Technologies.**

Other Glass Manufacturers

Other glass manufacturers you will be hearing about are:

- CDGM
- Ohara Glass
- Hoya Glass (Not popular in U.S.)
- Sumita Glass (Not popular in U.S.)
- Corning Glass – mainly for a type of glass called Fused Silica which is used in the UV Region



05.

Types of Optical Lenses

If you've ever seen a display of loose lenses, you know how visually captivating they can be, almost like a collection of jewels, in myriad sizes, shapes, weights, and colors. Lenses are, however, much more complex than they appear on the surface; the calculations and precise geometry that enable their sophisticated capabilities are invisible to the naked eye. This section offers a high-level view of a dozen different types of lenses, including simple, aspherical, doublets, triplets, and cylindricals. It explains the basic characteristics of each type, offers a few words about how a lens works and which applications it is suited to, and also includes simple illustrations of each to clarify some of the calculations necessary to effectively redirect light.

Simple Lenses
- » Equi-Convex or Bi-Convex Lenses
- » Equi-Concave or Bi-Concave Lenses
- » Plano-Convex lenses
- » Plano-Concave Lenses
- » Positive Meniscus Lenses
- » Negative Meniscus Lenses

Aspherical Lenses

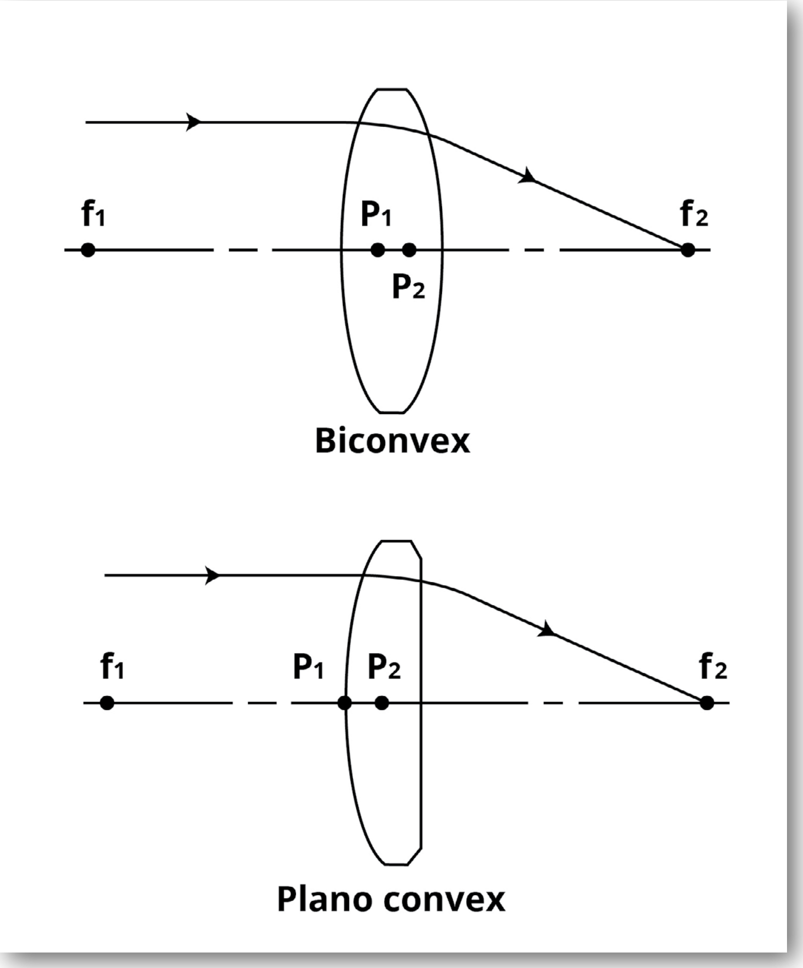
Doublets
- » Achromats
- » Aplanats

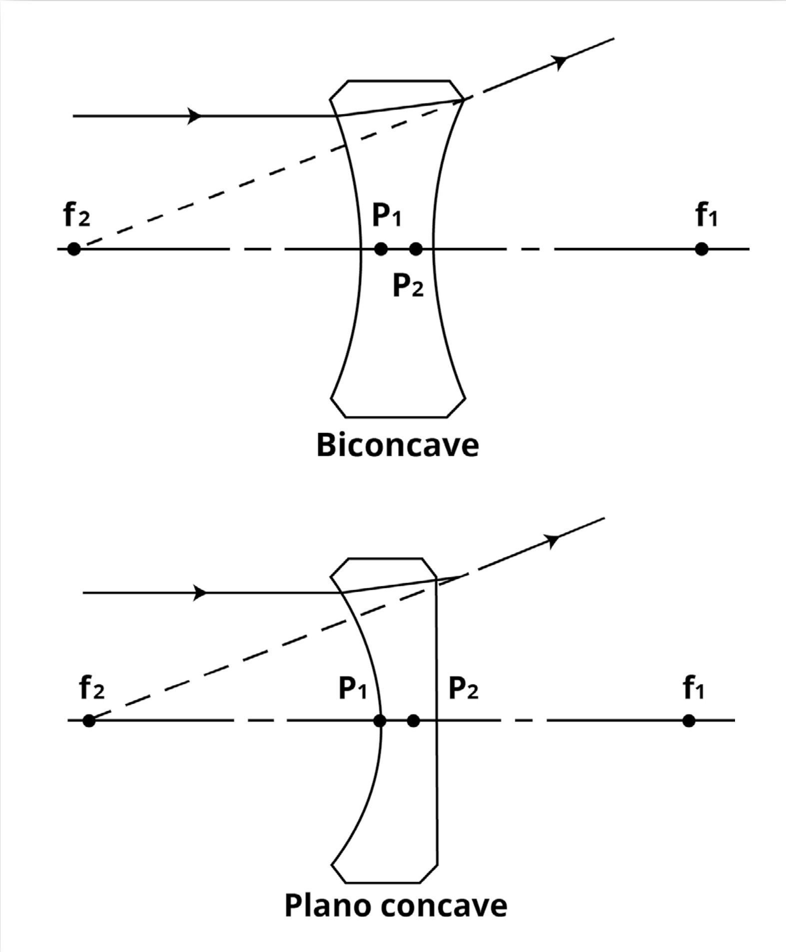
Cylindrical Lenses
- » Positive Cylindrical Lens
- » Negative Cylindrical Lens

Bi-Convex and Plano-Convex

Bi-convex lenses have positive focal lengths and form both real and virtual images. They are recommended for virtual imaging of real objects like in a magnifying glass.

Plano-convex lenses are always positive and are used to converge incident light. They should always be mounted with the flat side facing the focal plane. Used in many optical instruments including telescopes, collimators, magnifiers, radiometers, optical transceivers, and condensers.





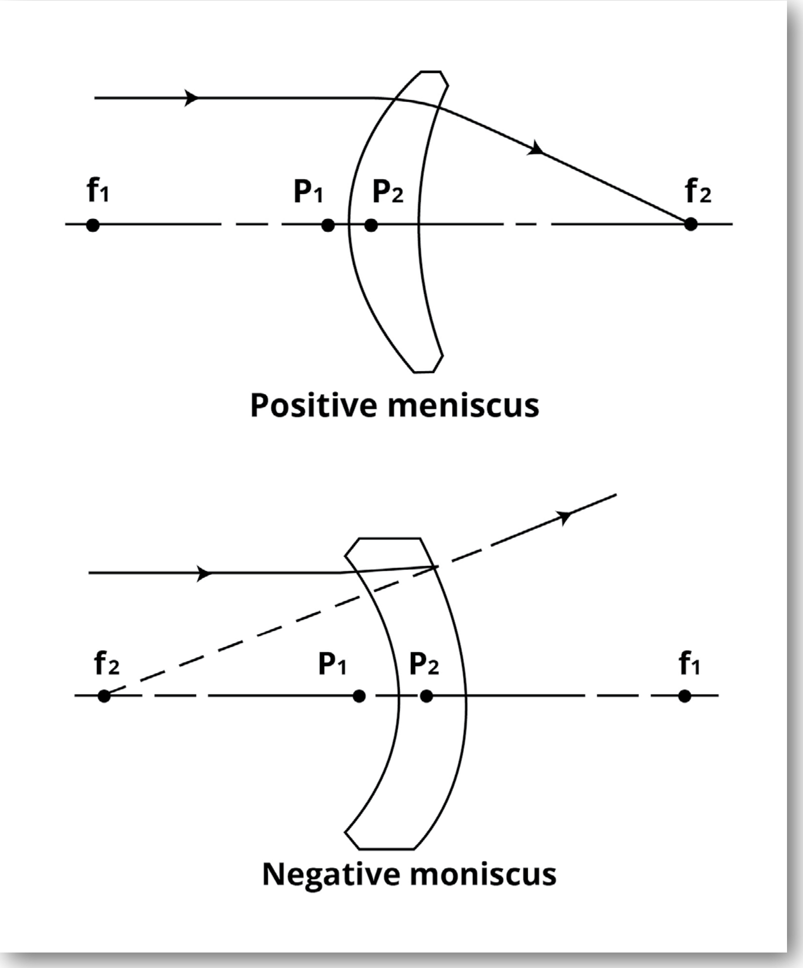
Bi-Concave and Plano-Concave

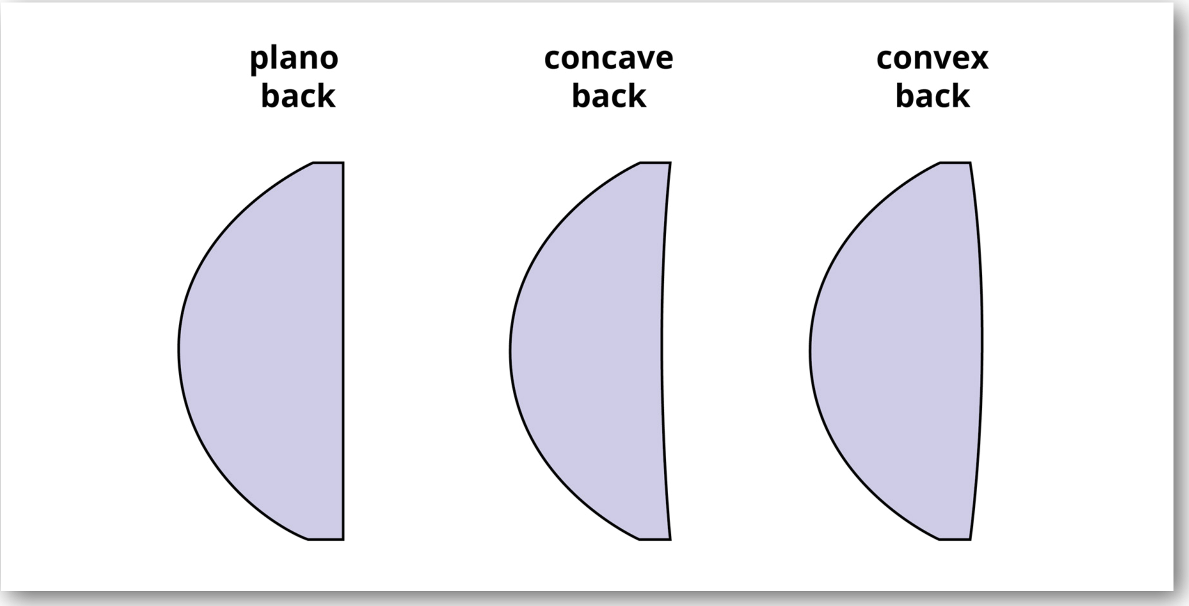
Bi-concave lenses have negative focal lengths and form virtual images, which are seen by looking through the lens. They are often used to expand light or to increase the focal lengths of existing systems. They are used in laser beam expanders, optical character readers, viewers, and projection systems.

Plano-concave lenses are always negative. They are used to diverge collimated incident light or to form virtual images which are seen by looking through the lens. They are often used to increase focal lengths in existing optical systems.

Meniscus Lens – Positive & Negative

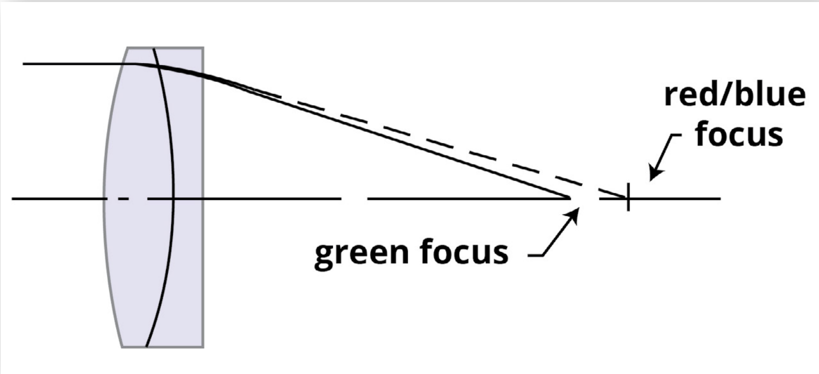
Meniscus glass lenses have one convex surface and one concave surface. They are used to change the focal length and effective f-number of another lens, without introducing additional spherical aberration or coma into the system.





Aspherical Lenses

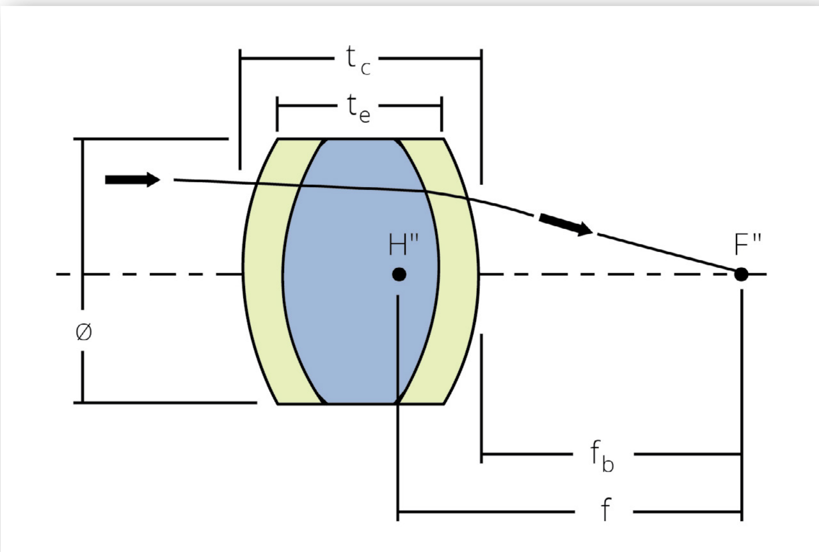
Aspheric lenses have at least one aspheric surface. In general, they provide better performance than spherical singlet lenses by reducing aberrations. They are ideal for use in low f-number, high-throughput applications. They are used extensively as condenser lenses in projection equipment.



Doublet – Achromatic & Aplanatic

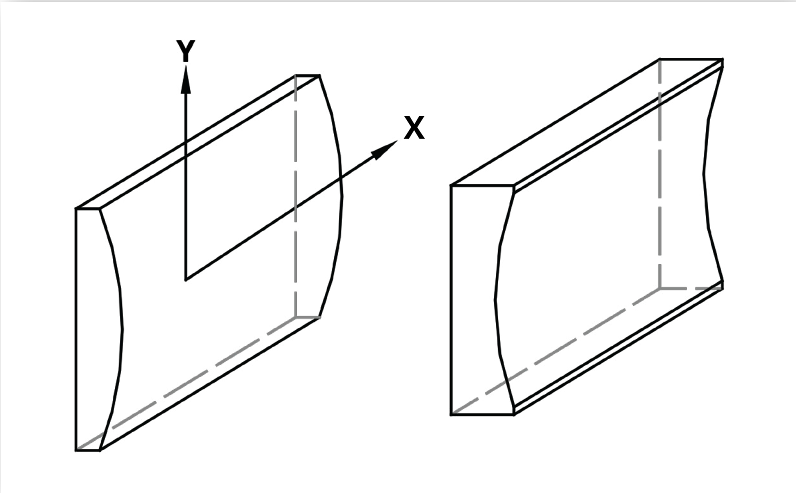
Achromatic lens is a closely spaced, often cemented combination of positive and negative elements with differing refractive indices. These elements are chosen so that chromatic aberration is cancelled at two distinct, well separated wavelengths. These wavelengths are usually selected to fall in the red and blue portions of the spectrum.

Aplanatic lens, similar to the achromatic lens, but also corrected for spherical aberration and coma.



Steinheil Achromatic Triplet

Steinheil achromatic triplets consist of a low-index, equiconvex crown glass element cemented between two identical high-index meniscus flint glass elements. These triplets are reversible (because they are symmetric) and perform well at conjugate ratios from 1 to 5.

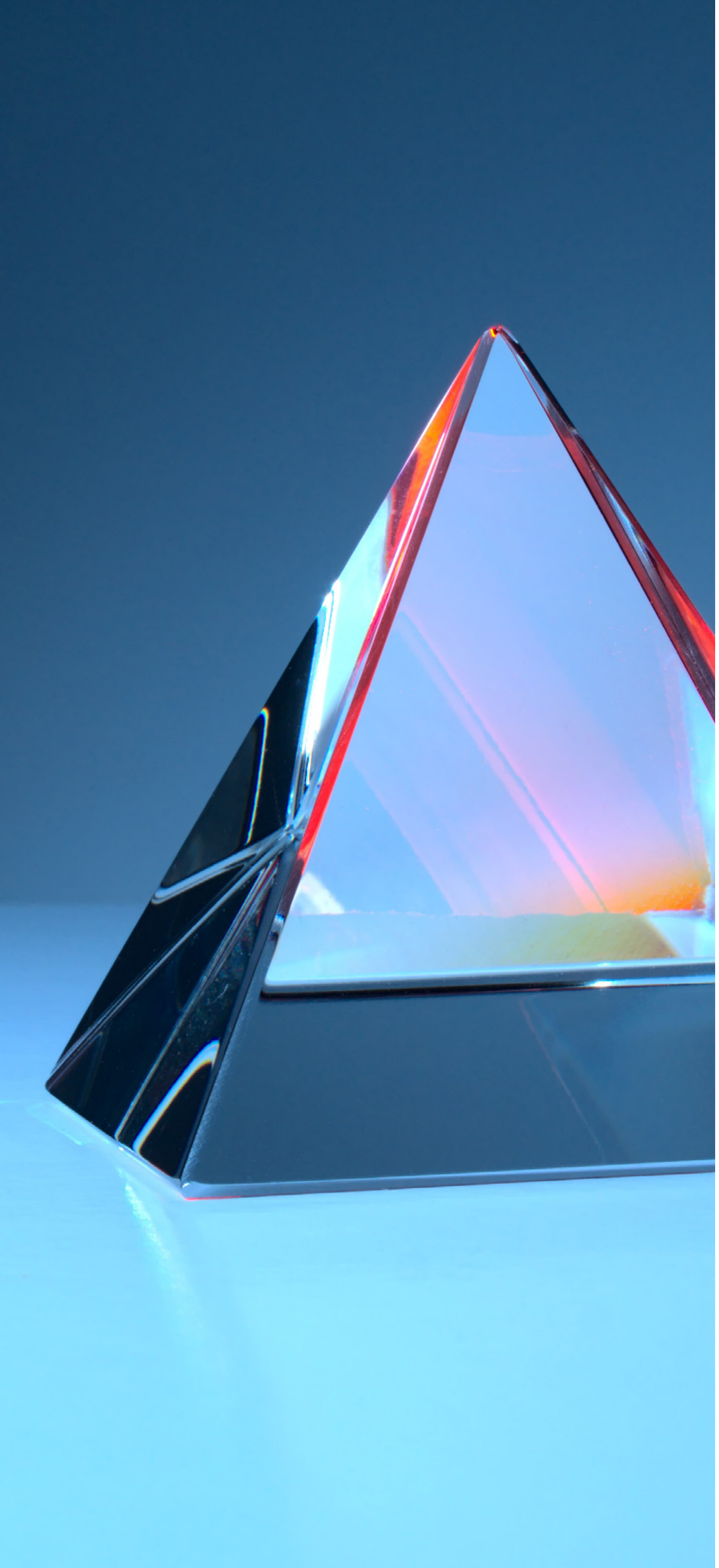


Cylindrical – Positive and Negative

Cylindrical lenses are used in applications requiring magnification in one dimension only. They are used to transform a point image into a line image and to change image height without changing width, or vice versa. Typical applications include slit and line-detector-array illumination.

Other Optical Elements

- **Windows**: Used to enable optical Light to pass from one environment to another without allowing the environments to mix. Available in round and square configurations with different qualities and materials (refer to catalog).
- **Mirrors:** Used to reflect a beam of light in different directions. Mirrors are available in a variety of sizes and shapes. In addition to shape and dimensions, the primary factors that need to be considered when specifying a mirror are: the reflective coating, the substrate material, the flatness or surface accuracy, cosmetic surface quality.
- **Prisms**
- **Beamsplitters**



06.
Prisms and Other Optical Elements

Beyond lenses, optics manufacturers are capable of designing and making other optical elements that include such things as windows, mirrors, prisms, and beamsplitters. This section briefly explains each element then takes a deeper dive into prisms, what they are and how they work. It includes easy-to-understand descriptions and useful diagrams of seven different types of prisms that Ross manufactures. At the end of the section, several types of beamsplitters are clearly illustrated and described.

Prisms

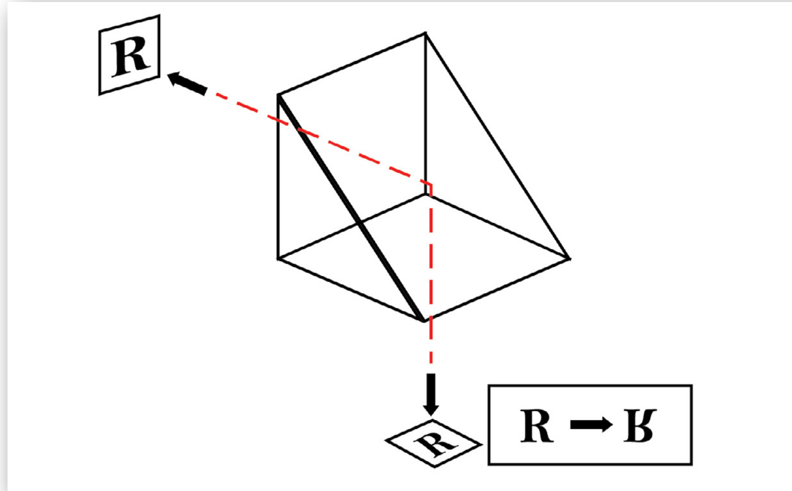
Prisms are blocks of optical material with flat, polished sides that are at precisely controlled angles to each other. Prisms may be used in an optical system to deflect or deviate a beam of light. They can invert or rotate an image, disperse light into its component wavelengths, and be used to separate states of polarization. Prisms will introduce aberrations when used with convergent or divergent beams of light. Using prisms with collimated or nearly collimated light will help minimize aberrations.

Types of Prisms

- » Right Angle Prisms
- » Equilateral Prisms
- » Dove Prisms
- » Roof (Amici) Prisms
- » Wedge Prisms
- » Penta Prisms
- » Retroreflectors

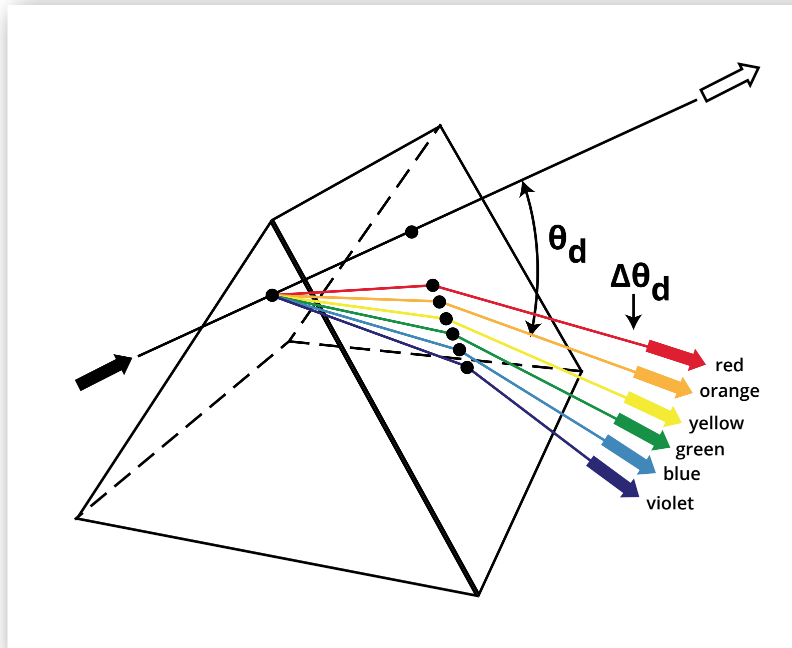
Right Angle Prism

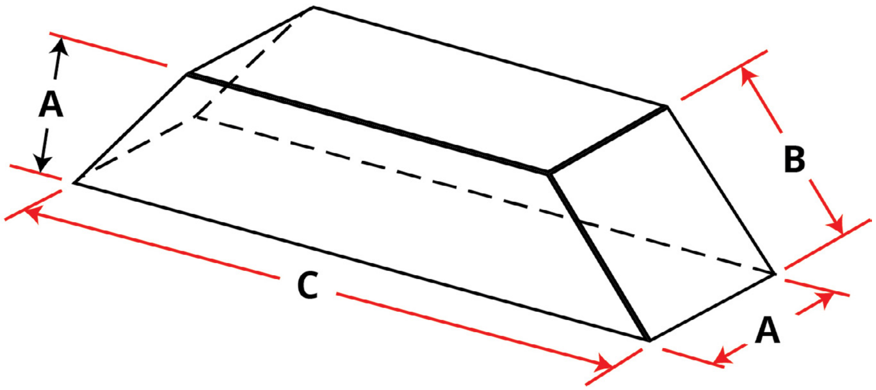
Right-angle prisms are used to direct a beam of light at 90 degrees from the incident. For collimated beams, the index of refraction for BK7 is sufficient to guarantee TIR (total internal reflection) at the hypotenuse for wavelengths in the visible and near infrared regions. A prism with an aluminized hypotenuse is recommended for applications where the prism is frequently handled, or where convergent or divergent beams are used.



Equilateral Prisms

Equilateral or dispersing prisms are used to separate wavelengths. A light ray is refracted twice as it passes through the prism.

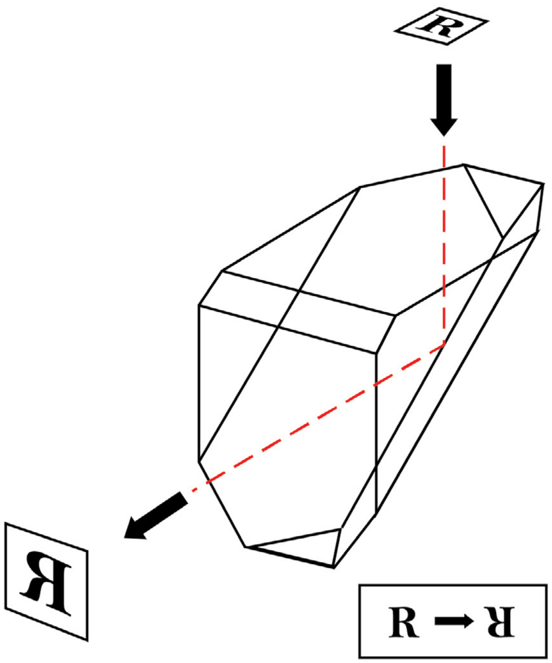


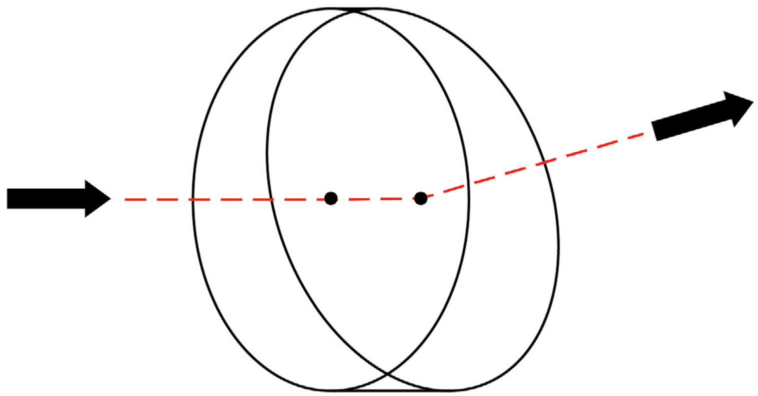


Dove prisms are used as image rotators. As the prism is rotated, the image passing through will rotate at twice the angular rate of the prism. Dove prisms are used with parallel or collimated light. Dove prisms are normally used in a TIR (total internal reflection) mode with the hypotenuse (longest) face unaluminized.

Roof (Amici) Prism

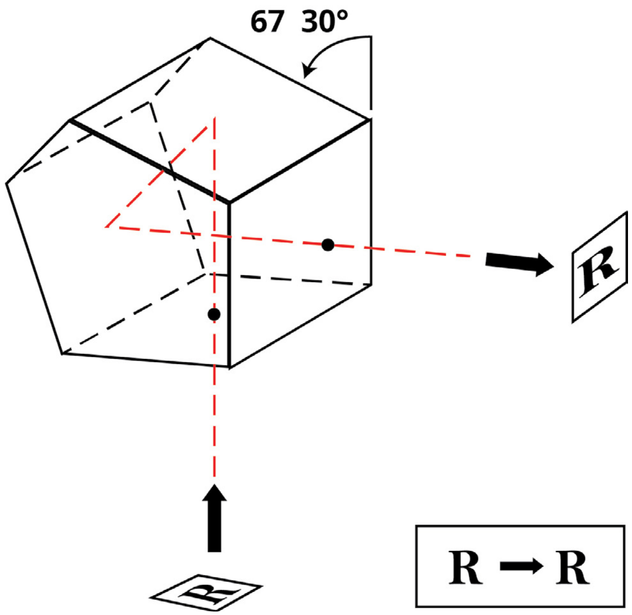
The roof (or Amici) prism deviates or deflects the image through an angle of 90 degrees. It is a right-angle prism whose hypotenuse has been replaced by a 90-degree roof. Glass that does not contribute to the clear aperture has been trimmed away to reduce size and weight. Roof prisms are suitable for applications that demand both right-angle deflection.





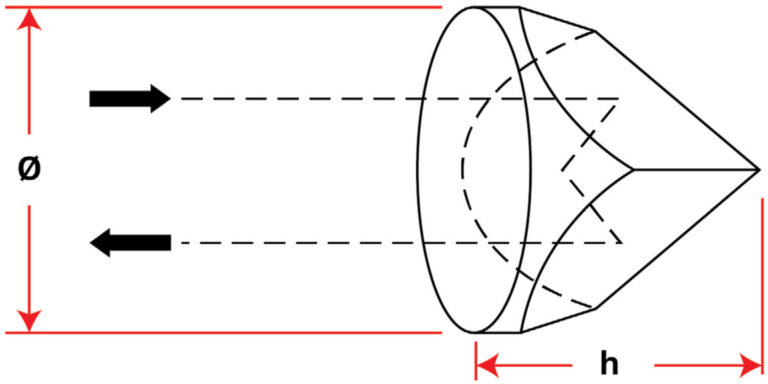
Wedge Prisms

Wedge prisms deviate an incident beam at a precise angle.



Penta Prisms

Penta prisms deviate beams by 90 degrees without changing the orientation of the resulting image.



Retroreflectors

Any ray entering the effective aperture of a retroreflector will be reflected and emerge from the entrance/exit face parallel to itself, but in the opposite direction of propagation

Beamsplitters

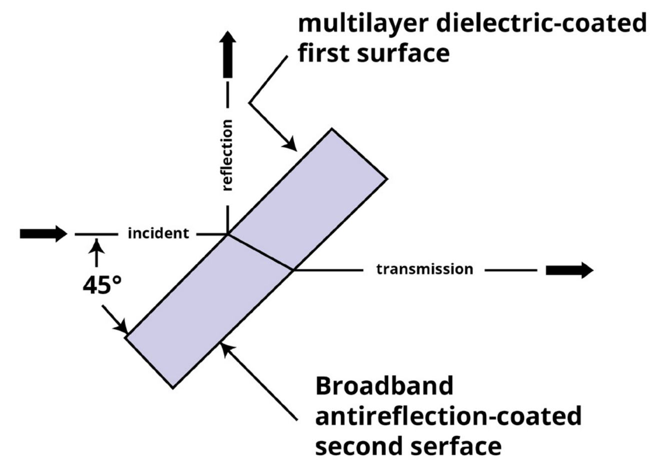
A beamsplitter is used to separate the light beam into two directions—one transmitted and the other reflected. There are two kinds of beamsplitters – **plate beamsplitters and cube beamsplitters**

Cube beamsplitters have several advantages over plate beamsplitters:

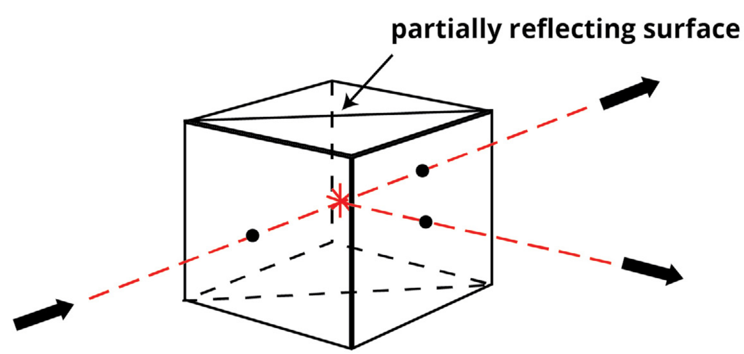
» They are easier to mount
» They are ideal for beam superposition
» They exhibit less ghosting
» Mechanical stress causes less deformation
» The coatings are less likely to degrade over time because they are sealed into the body of the cube

Plate beamsplitters introduce astigmatism if the light isn't collimated.

Plate Beamsplitters



Cube Beamsplitters



07. Coatings

Nearly all optical elements require some type of coating or thin film. The coating serves a dual purpose; it protects the optic and it improves performance. Depending on the application, a coating will either minimize reflectance (for lenses) or increase it (for mirrors). This section explains the characteristics of popular coatings and describes some of our capabilities. It also introduces basic yet important terminology; describes the various ways that coatings are manufactured and applied; discusses coatings for specific wavelengths; and provides a brief but useful analysis of several types of antireflective and high reflectivity (metallic) coatings. There are also a few words on coatings for beamsplitters.

Optical Coatings

When light passes through different mediums, a percentage of the light is reflected and a percentage of the light is transmitted. The amount of light that is reflected versus the amount transmitted depends mainly on the refractive index of the medium and the angle of incidence of the light. For a standard glass like BK7, at normal incidence, approximately 4% of the light is reflected and 96% is transmitted.

Optical Coatings are used to modify the reflectance and transmission properties at the surface of the optical element. In principle, the surface of the optical element is coated with various layers of materials (called thin films) in order to insure the reflection/transmission ratio. The type of thin film that is applied and the number of layers applied to achieve the desired reflection/transmission ratio is dependent on the material of the optical element, the incident angle of the light and the wavelength at which the element is being used.

Coatings Manufactured at Ross

Coatings are manufactured by two processes at Ross:

- » Dielectric coatings (using chemicals like Magnesium Fluoride MgF_2, Hafnium Oxide HfO_2)
- » Metallic Coatings (using Metals like Aluminum, Gold, Silver)

Following is a partial list of coatings being done at Ross. The following pages will describe each coating:

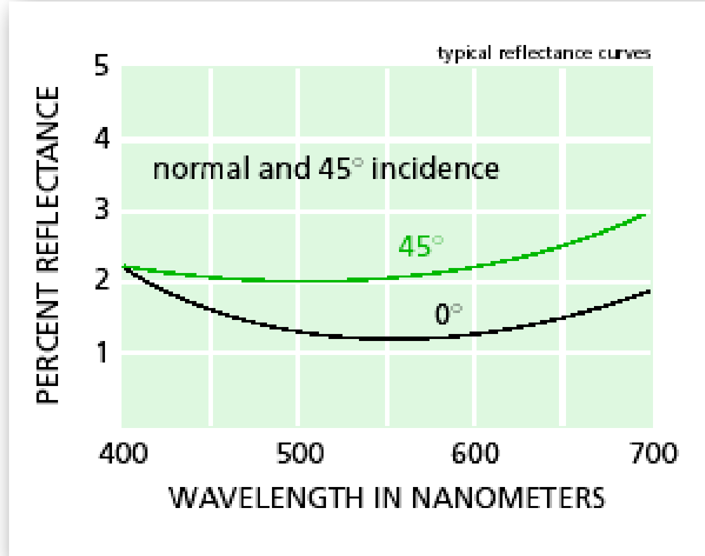
- » Single Layer MgF_2
- » Broad Band Anti-Reflection (BBAR)
- » "V" Coating
- » High Reflection Dielectric Coatings (Mirrors)
- » Protected Metallic Coatings (Mirrors)
- » Beamsplitter Coatings

Coating Deposition

There are different deposition processes for coatings, the main ones being the Resistive Process, Electron Beam Deposition and Sputtering. At Ross, the Resistive process is used for Metallic coatings and Electron Beam Deposition is used for Dielectric Coatings.

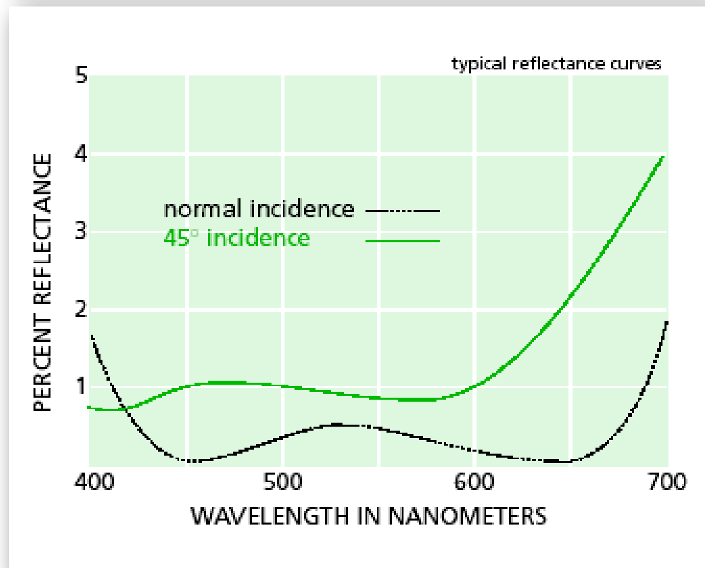
Single Layer Magnesium Fluoride MgF_2

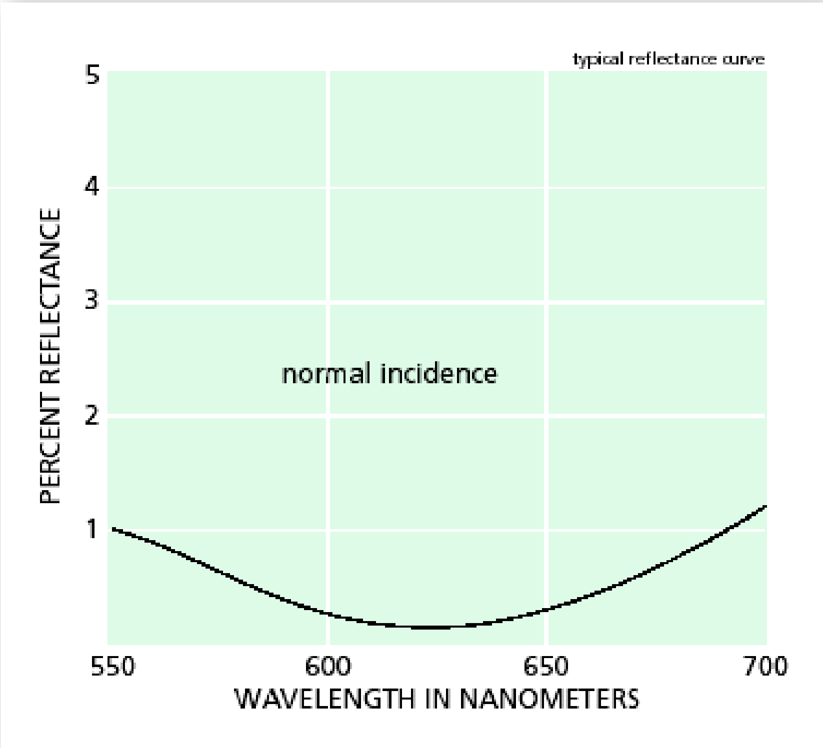
- Most widely used thin film coating
- Though the performance is not outstanding, it provides a significant improvement over bare glass
- A coating of MgF_2 can reduce the reflectance loss from 4% to 1.5% for BK7
- Cheaper if the application does not require a high quality coating and can stand some reflection losses, as it is only one layer



Broad Band Antireflection Coating BBAR

- Provide a very low reflectance over a broad wavelength region usually in the order of 200nm (typical visible coatings range from 450-650 nm)
- Reduces the reflectance of the uncoated surface from 4% to an average of 0.5% over the entire region





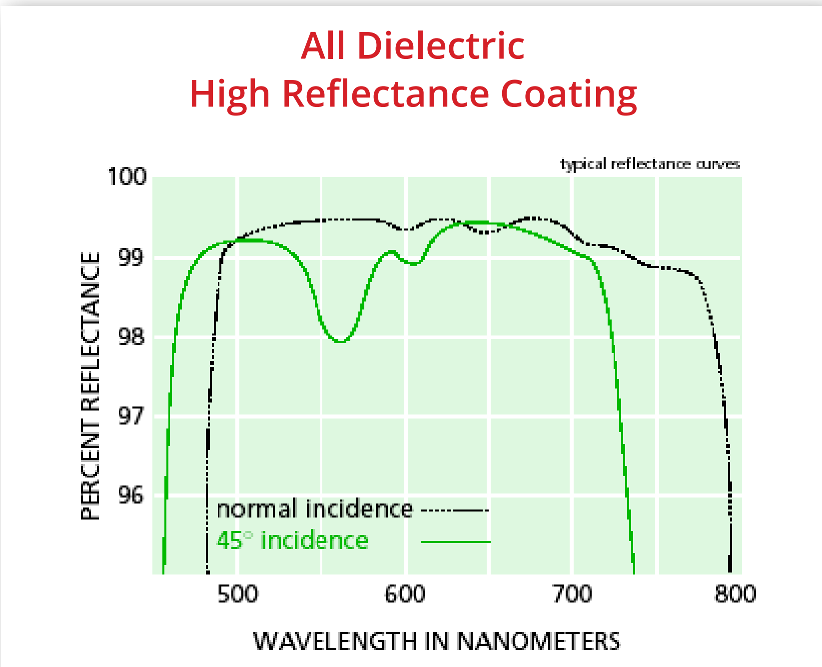
V-Coats

- V-Coatings are multi-layer anti-reflection coatings that reduce the reflection of the optic surface to near 0% for one very specific wavelength
- This kind of coating is mainly used for laser applications, where any kind of reflection from the surface of the optic will cause ghost images
- At Ross we do V-Coatings for any wavelength requested between 390 to 2500 nm

High Reflection Coatings

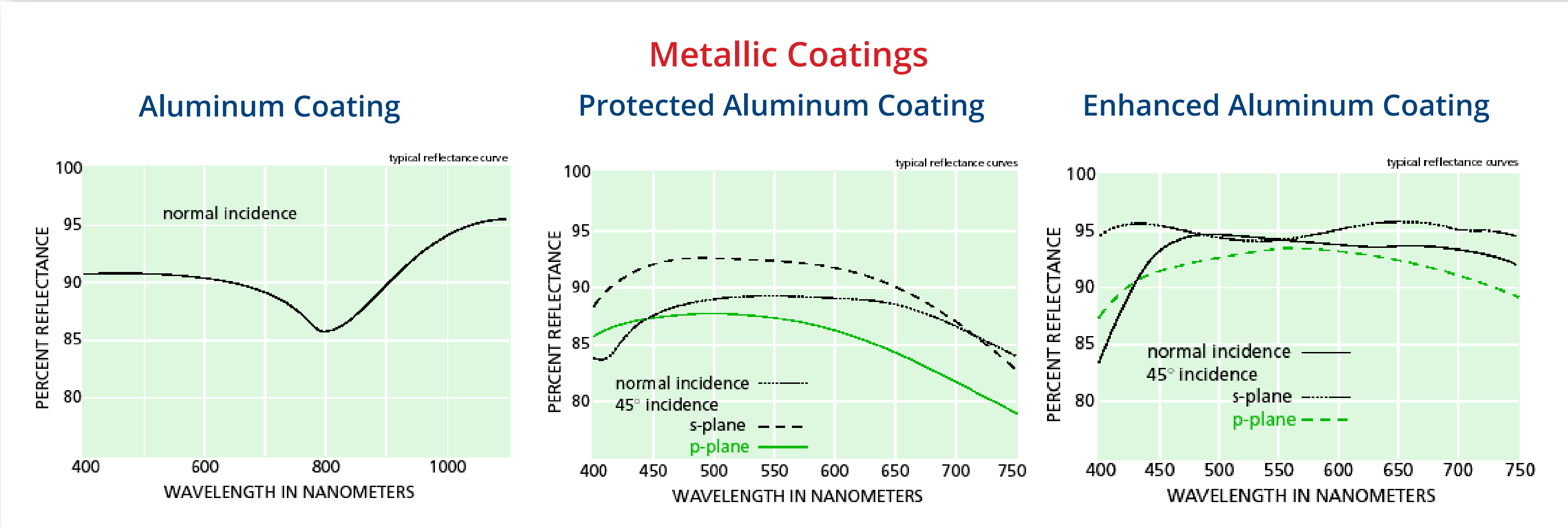
Depending on the coating chemicals, it can be single layer (such as aluminum mirror), to multi-layer dielectric.

> **Three types: All Dielectric, Metallic, Hybrid**



You will hear mostly terms like:

- **Aluminum mirror:** One layer Al coating, R is about 92%
  - *The Aluminum will oxidize over time*
- **Protected Al mirror:** Al coating with SiO overcoat, R 85 to 90%
  - *Preferred because the SiO dielectric layer arrests the oxidation*
- **Enhanced Al mirror:** Al layer with about 6 more dielectric layers
  - R is 90 to 95%
- Gold mirror, silver mirror
- Second surface mirror, or first surface mirror



Protected Aluminum

This is the most popular form of Aluminum mirror. The protection layer can be any chemical. Most popular is Silicon Monoxide (SiO) (as we do it at Ross). Metallic mirrors do not transmit light. They reflect most of the light, and the metallic layer absorbs the rest. The reflection can be from 85 to 90%.

Beamsplitter Coatings

We do the all dielectric beamsplitter (there are metallic beamsplitters). You will often hear the terms:

- Reflection/transmission ratios (R/T) of 50-50, 30-70, 70-30 etc. Attention must be paid to which number is transmission and which number is reflection
- Incident angle can be 0°, 45° or any other number
- Wavelength can be over a range like 450-650 nm, or a single wavelength like 633 nm

The Ross team is here to help you with all of your questions regarding purchasing optics.

Contact us today!

rossoptical.com

Check out additional resources from our team

rossoptical.com/resources

References

photonics.com/Dictionary