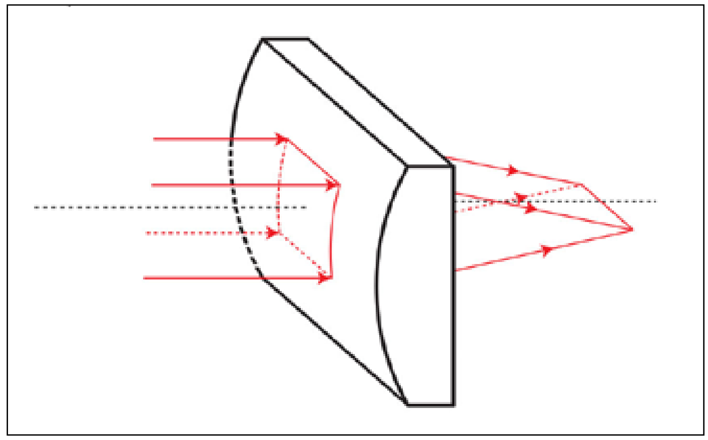
How to Select Cylindrical Lenses

Cylindrical lenses act on light to converge or expand it much like spherical lenses do, but in only one dimension. This makes them useful for altering the proportions of an image, either singly or when used in pairs. They can transform a point image into a line image or change the height of an image without altering its width (or vice versa). Applications of this type include anamorphic beam shaping and correcting the elliptical output of a laser diode to create a circular, collimated beam. Cylindrical lenses are used in the source assemblies of many systems, where they generate a line output from a laser. They are also used to gather and focus light onto a linear detector, or for coupling into a slit, as in spectroscopy applications.



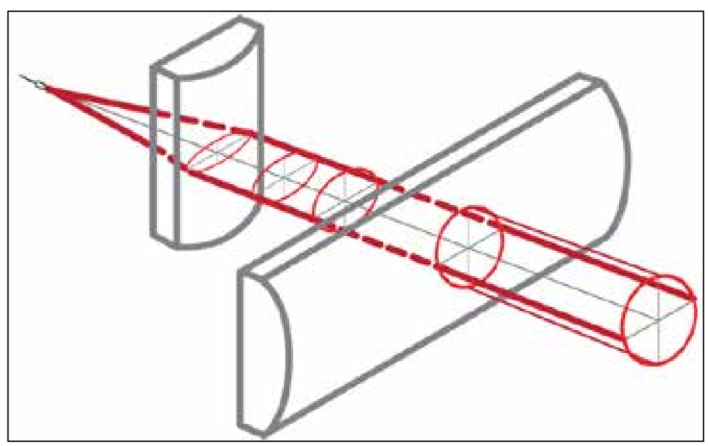
Drawing 1: How the plano-convex lens can be used to focus collimated light to a thin line.

Cylindrical lenses are governed by the same theory and formulas as spherical lenses, although they image in one dimension, not two. Many of the benefits and guidelines for plano-convex and plano-concave spherical lenses regarding aberrations and conjugate ratios are therefore applicable to cylindrical lenses. For a complete discussion of lens theory, use, and aberrations please refer to the Fundamental Optics and Gaussian Beam Optics sections of the Technical Guide.

Lens Types

Plano-convex cylindrical lenses can be used for magnification or to condense light in a single dimension. They can focus light to generate a thin line for use in laser scanners, pumping of dye lasers, acousto-optics, and optical computing. As for spherical lenses, the plano-convex design minimizes spherical aberrations for conjugate ratios greater than 5:1, with best performance when collimated light is incident on the convex side. These positive lenses are also ideal for energy collection for illumination of linear detector arrays or coupling to a slit input.

While plano-convex cylindrical lenses are often used to converge or focus light into a line, they can transform a point of light into a line image, which makes them useful to generate line sources or for anamorphic beam shaping. Plano-convex lenses are often used in perpendicularly oriented pairs for collimation and circularization of diode laser outputs. The lens closer to the laser collimates the fast axis, while the second lens collimates the slow axis of the laser diode. Using two distinct lenses in this way also permits complete removal of the astigmatism inherent in laser diodes.



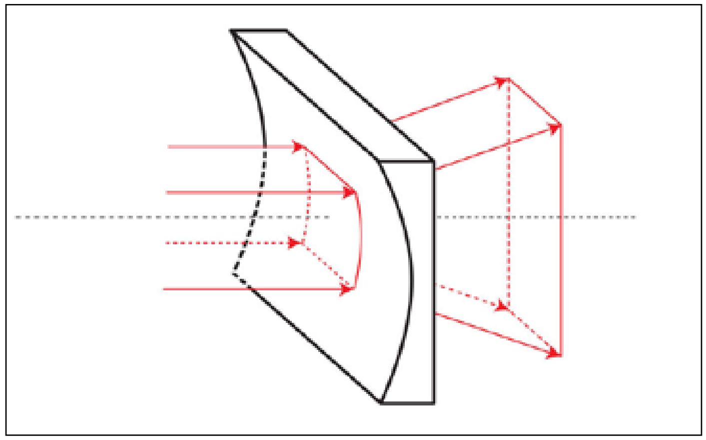
Drawing 2: How the cylindrical lenses are used for collimation and circularization of diode laser outputs

Plano-concave cylindrical lenses diverge or expand light in a single dimension. They are used to project a collimated laser to create a diverging line output (laser line generators). Spherical aberrations will be minimized when collimated light is incident on the concave side. They can also be used as a mirror blank when a concave cylindrical surface is required.

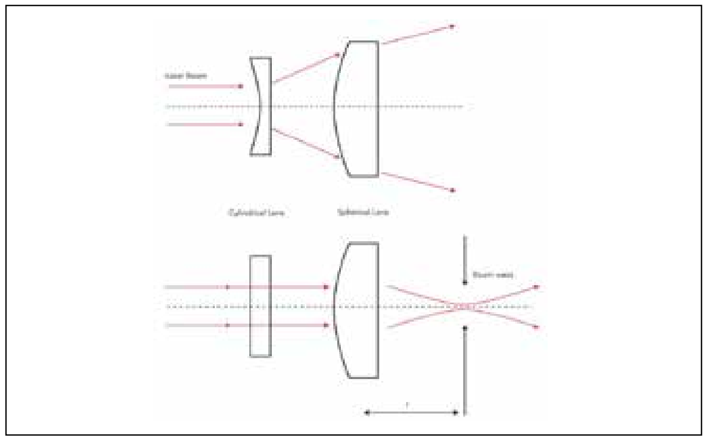
A combination of lenses is used in many optical systems to correct the shape of laser beams, change the aspect ratio of an image, as well as to generate line sheets or produce line images. In anamorphic beam shaping, a common design is to use both plano-concave and plano-convex cylindrical lenses in a beam expander configuration. Anamorphic lenses are often used in the film industry to distort an image to allow standard 35 mm films to record images in widescreen format. They can also enable 16:9 aspect ratio digital projectors to create fullscreen 2.35:1 (Cinemascope) images for display on super-wide format home-theatre screens. By attaching an anamorphic lens to the projector in front of its standard lens, the image first electronically stretched in the vertical direction is returned to its original aspect ratio and appears optically undistorted. Black bars are not needed above and below the image, which is displayed with higher resolution and brightness.

Light sheet generators, which are used in several optical measurement techniques like particle image velocimetry, planar laser-induced fluorescence and flow visualization studies, utilize various combinations of spherical and cylindrical lenses to achieve the proper light sheet. This depends on the required projection distance, laser sheet thickness, depth of field, and on the laser characteristics. A typical configuration to generate a divergent light sheet is shown below. A collimated laser beam is first expanded in one direction only using a plano-concave cylindrical lens, then a spherical lens is used to focus the beam in the perpendicular direction, compressing the light into a thin sheet.

Laser projection, scanning, and printing systems also use various combinations of plano-concave and/or plano-convex lenses.



Drawing 3: How a plano-concave lens can be used to create a (diverging) light output to spread light



Drawing 4: How a light sheet can be generated

Lens Materials

Aside from lens shape, the material a lens is made from has the greatest impact on its performance. Not only does it determine the transmission properties, refractive index, laser damage threshold, thermal properties, durability and weight, but it also impacts cost. It even imposes practical limits on manufacturing tolerances, especially surface cosmetic quality. CVI Laser Optics utilizes N-BK7 and UV-grade fused silica to manufacture our catalog cylindrical lenses, but other materials are available on a custom basis, including CaF_2, MgF_2, ZnSe, Si, and Ge. We can also manufacture many of our lenses with custom dimensions and focal lengths.

N-BK7 is a lead- and arsenic-free borosilicate crown glass that is used widely in the optics industry. It has broad transmission from 350 nm – 2.0 μm, good homogeneity and low bubble content and is relatively low in cost. It is a hard glass that stands up well to handling, with good chemical resistance. N-BK7 polishes extremely well, and surface quality of 10-5 or 20-10 scratch and dig can be achieved. It provides high performance and damage resistance for VIS-NIR applications in the range 400 – 1600 nm. When better thermal stability, higher damage threshold, superior transmission or UV operation is required, we recommend using substrates made from UV-grade fused silica.

Our UV-grade fused silica is Corning 7980, a fused silica (synthetic amorphous silicon dioxide) manufactured by flame hydrolysis to extremely high standards. Its high quality and purity is evident in the wide transmission range of 185 nm – 2.1 μm and its high laser damage threshold. It does not fluoresce in response to wavelengths longer than 290 nm, and in general exhibits good resistance to radiation darkening from ultraviolet, x-rays, gamma rays, and neutrons. It has good mechanical properties, with increased hardness and resistance to scratching, and polishes extremely well. It also boasts excellent thermal properties, including a wide operating temperature range, low thermal expansion coefficient, and resistance to thermal shock. This makes UV-grade fused silica ideal for applications requiring high UV transmission, thermal stability and mechanical robustness, and high laser damage threshold in the UV and VIS-NIR wavelength range. Other types of fused silica such as Suprasil 1, as well as fused quartz with low OH content are available on a custom basis. Please contact CVI Laser Optics for additional information.

Lens Quality

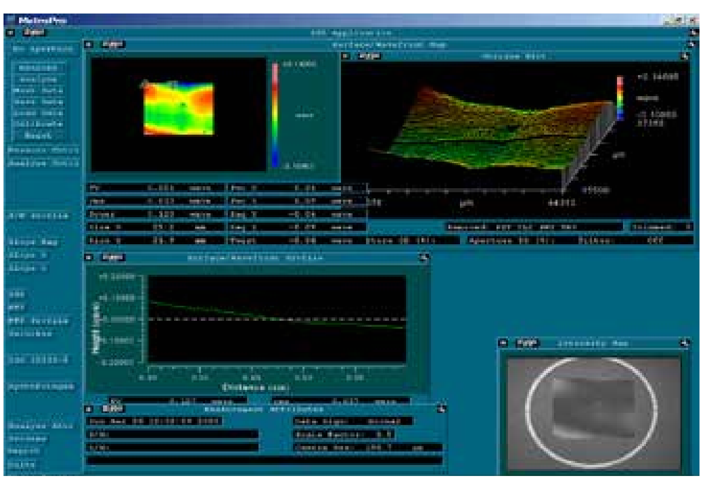
Once the lens shape and material has been selected, the next step is to determine the lens quality required. This will depend on the application and performance needed, but factors to consider include laser damage threshold, degree of scatter, surface figure, lens centration and wedge, and focal length tolerance.

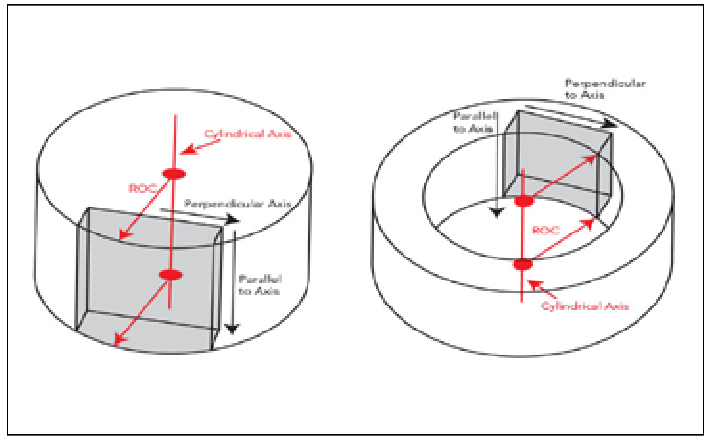
Our standard cylindrical lenses are manufactured to a surface quality of 60-40 scratch and dig from N-BK7 glass. They are an economical solution for applications where lens wedge and surface accuracy are not critical parameters, but laser damage threshold is not as high. These lenses are available uncoated, or with choice of visible or near-infrared broadband antireflection coatings.

	N-BK7	UV-grade fused silica
Transmission Range	350 nm - 2.0 μm	185 nm - 2.1 μm T_i > 88%/cm @185nm
Index of Refraction (n_d)	1.519 @ 546.1 nm	1.46 @ 546.1 nm 1.509 @ 248 nm
Abbe Number (v_d)	64.17	67.79
Coefficient of Thermal Expansion ($x10^{-6}$/°C)	7.1	0.57
Knoop Hardness (kg/mm^2)	610	522
Cost	Low	Moderate
Main Features	High transmission for visible to NIR; good mechanical and optical properties; the most common optical glass	Superior UV transmission, excellent homogeneity and low thermal expansion coefficient; higher damage threshold than N-BK7

Our laser quality lenses differ from standard lenses in two key respects. First, high cosmetic surface quality (20-10 scratch and dig) and low surface roughness make them more suitable for high energy laser applications and/or for applications where scatter must be reduced for better signal to noise performance. Second, precise polishing to high surface accuracy and tighter paraxial focal length tolerance yields the low wavefront distortion and accuracy required for use in ultra-violet and performance-critical applications. Tighter centration and wedge tolerances also result in straighter lines and better quality images. The term "laser quality" therefore refers to both high laser damage threshold and to higher performance specifications. CVI Laser Optics manufactures our catalog laser quality cylindrical lenses from N-BK7 and UV-grade fused silica.

It is important to note that our laser quality optics are tested to extremely high standards. We perform 100% visual inspection for cosmetic surface quality on all optics. We inspect using significantly brighter light sources than the 40 W light source required per MIL-PRF-13830B, and use high power magnification, making defects much more readily visible. The resulting surface quality is therefore much better than the industry standard. Our laser grade optics are virtually defect-free. Our choice to inspect using more rigorous methods than are strictly required reflects our commitment to excellence in manufacturing. This proprietary inspection method was actually developed to consistently meet our customers' laser induced damage requirements, and reflects our extensive experience in delivering high LDT optics.





Drawing 5 & 6: Cylinder representation showing the dimensions perpendicular and parallel to the cylindrical axis

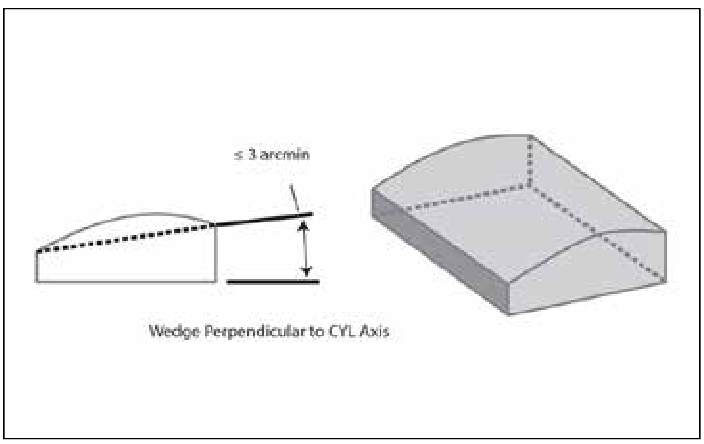
All of our laser quality lenses are available with a wide range of broadband, dualband 1064/532, and narrowband V-coat antireflection coatings at wavelengths from the UV through near-infrared. These AR coatings offer high durability and damage threshold, low loss, and peak performance when applied to laser quality optics. For best laser damage threshold performance, we recommend V-coat antireflection coatings on laser quality 20-10 fused silica substrates.

Surface form and centering errors

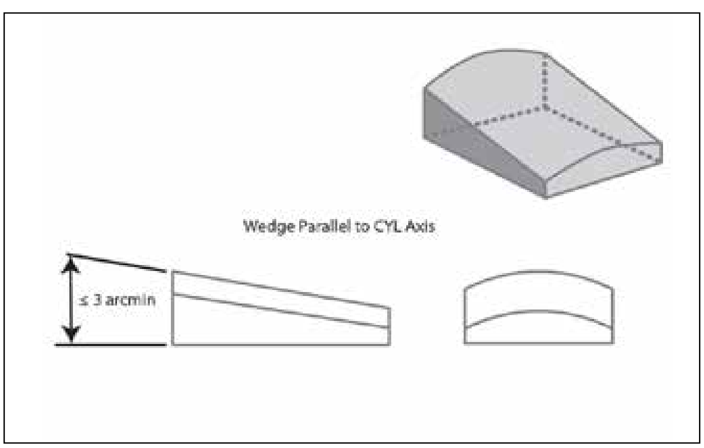
A discussion of lens quality would not be complete without an explanation of the specifications describing surface form and centering errors for cylindrical optics. Due to their asymmetry, two key dimensions are used to describe a cylindrical plano-convex or plano-concave lens: the parallel and perpendicular directions. The surface is flat in the direction parallel to the cylindrical axis, and has a radius in the direction perpendicular to the cylindrical axis, as shown in the figures below. These parallel and perpendicular characteristics aid in understanding the various specifications called out. CVI Laser Optics' specifications define length as the dimension along the parallel direction (x-direction) and width as the dimension along the perpendicular direction (y-direction), even if the length happens to be smaller than the width.

Surface figure (or form error) for the plano surface is simply specified in terms of flatness, or how the surface deviates from a perfect flat, as it is for other optics. In the case of the curved surface, the surface figure represents the

	Standard	Laser Quality
Clear Aperture	≥ 90%	≥ 85%
Surface Figure, flat surface (p-v @ 633 nm before coating)	Not specified	λ/4 flatness
Surface Figure, curved surface (p-v @ 633 nm before coating)	Not specified	y-direction (width): λ x-direction (length): λ/cm
Surface Quality (both sides)	60-40 scratch and dig per MIL-PRF-13830B	20-10 scratch and dig, CVI Laser Quality
Dimension tolerance	± 0.6 mm	+0 / -0.25 mm
Center thickness tolerance	± 0.6 mm	± 0.25 mm
Wedge ($\Delta t_c/x$)	≤ 8 mrad	≤ 3 arc minutes
Centration	Not specified	< 3 arc minutes (edge thickness difference)
Paraxial focal length tolerance	± 2%	± 0.5%
Design wavelength	N-BK7: 587.6 nm	N-BK7: 1064 nm Fused silica: ~ 248 nm
AR coating	Optional, wavelength user-specified Limited offering of BBAR coatings	Optional, wavelength user-specified All standard CVI AR coatings available
Damage threshold	Suitable for low to medium energy lasers	10 J/cm^2, 20 nsec, 20 Hz @ 1064 nm



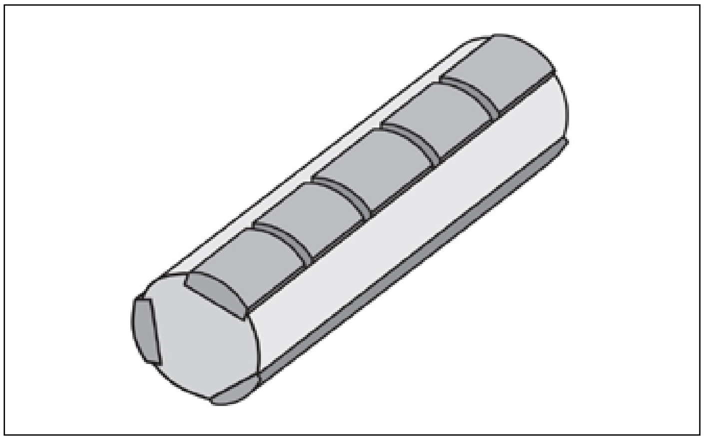
Drawing 7: Centering errors that can be generated by improper blocking



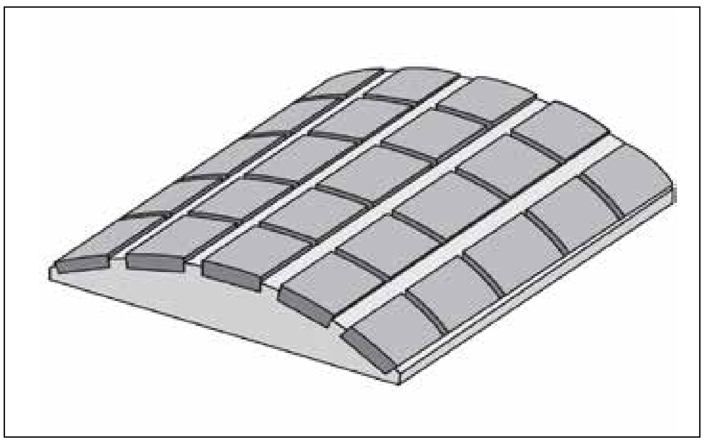
Drawing 8: Centering errors that can be generated by improper blocking

deviation of the part from an ideal cylinder shape, similar to the irregularity specification for spherical surfaces, which quantifies the deviation of the part from a perfect sphere. It includes the unwanted power (or curvature) in the parallel direction, but does not include the power in the direction perpendicular to the cylindrical axis. This power in the perpendicular direction, which is a measure of how closely the average cylindrical radius of the part under test matches the specified radius, is specified separately, and is reflected in the tolerance on the focal length of the part. The surface figure for the cylindrical surface is usually quoted separately along the parallel and perpendicular directions. We specify it per cm of the lens' length along the x (parallel) direction, and over the whole width aperture along the y (perpendicular) direction. All values are measured peak to valley (p-v) at 633 nm using a Zygo interferometer and computer-generated hologram (CGH), as shown below.

Centering error is also more complex to describe for a cylindrical lens, as it lacks the symmetry of a spherical lens, and because the optical axis is a plane rather than a line. Centration describes the centering error in the direction perpendicular to the cylindrical axis, which can be compensated for by adjusting the lens downward, or by edging the lens down, just as for the spherical lenses. Centration (edge thickness difference) for our laser quality cylindrical lenses is < 3 arc minutes. Wedge is the centering error in the parallel direction, and corresponds to the angle between the cylindrical axis and the plano



Drawing 9: Barrel blocking lens production mount



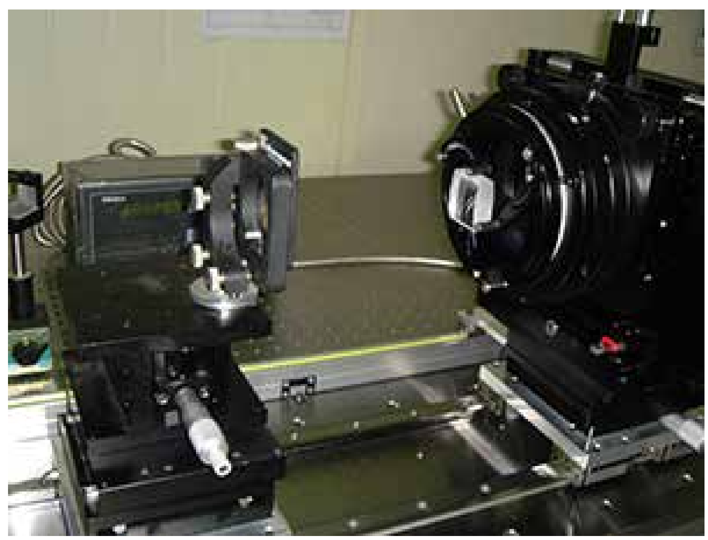
Drawing 10: Plate blocking lens production mount

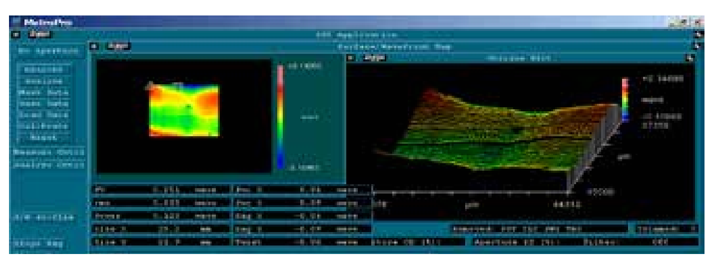
surface of the lens. Correcting the wedge in the parallel direction, however, would require re-surfacing the back plano surface. Wedge ($\Delta t^c/x$) for our laser quality cylindrical lenses is < 3 arc minutes, as compared to ≤ 8 mrad for our standard quality lenses.

Manufacturing and testing of cylindrical lenses

Two primary methods of polishing are used at CVI Laser Optics. In the rotary method, a cylinder rod is rotated about its axis. Barrel blocks with short radius convex cylinders mounted on them are polished in this manner. Concave lenses can also be surfaced this way when mounted on a plate block with a rotating polishing tool. In the Strasbaugh or linear method, plate blocks of lenses are polished. This can be seen as a variation of the equivalent process used for making spherical optics, where an axis of the lap is constantly maintained in parallel with the axis of the cylinder surface. Which method is used depends on various specifications of the part, such as required surface figure, edge dimensions and the radius of curvature. These traditional lens fabrication methods have been refined at CVI Laser Optics; through the hands of our highly skilled technicians, our expertise in these polishing processes and careful control of techniques enables us to produce high performance optics. Our polishing processes and manufacturing techniques allow us to consistently produce low scatter, laser quality optical surfaces, which combined with our ultra-hard coatings, result in high damage threshold optics.

We carry out 100% inspection on all surfaces, cleaning and examining them at each stage of the manufacturing process. Upon completion, we use interferometry techniques to individually measure the surface figure and cylindrical radius of each final part. The test plates are also tested interferometrically, which ensures high quality control in the manufacturing process.





The surface figure of all cylindrical surfaces is tested with computer-generated holograms (CGH) along with a Zygo GPI interferometer. Using a CGH in transmission in front of the interferometer generates an accurate cylindrical test wavefront that matches the curvature of the surface under test, and thus gives a precise measurement of the surface figure over the entire cylindrical surface. Precision up to $\lambda/10$ p-v can be achieved. Obtaining precise, accurate, and repeatable metrology is essential for guaranteeing high-quality components. A typical measurement configuration using computer generated holography as well as the corresponding Zygo report with full surface map are shown below. Mechanical specifications such as wedge are verified using micrometers and microscopes, or by optical methods using autocollimators.

Making the final decision

Shape and curvature of your cylindrical lens will be based on the beam propagation requirements, while size selection is determined by beam size requirements. If choosing the right cylindrical lens seems challenging, remember that CVI Laser Optics applications engineers are available to provide a ray-tracing analysis of simple catalog-component systems. If choosing the right cylindrical lens seems challenging, remember that CVI Laser Optics applications engineers are available to guide you through the process.

Numerous other factors, such as lens manufacturing tolerances and component alignment, impact the performance of an optical system. It should be kept in mind that if calculations indicate that a lens system only just meets the desired performance criteria, in practice it may fall short of this performance as a result of other factors. In critical applications, it is generally better to select a lens whose calculated performance is significantly better than needed.

If our wide array of catalog and semi-custom lenses available with your choice of AR coatings do not offer quite the right fit for your application, we can customize a cylindrical lens to your exact dimension, material, and AR coating needs.

Selection Guide: