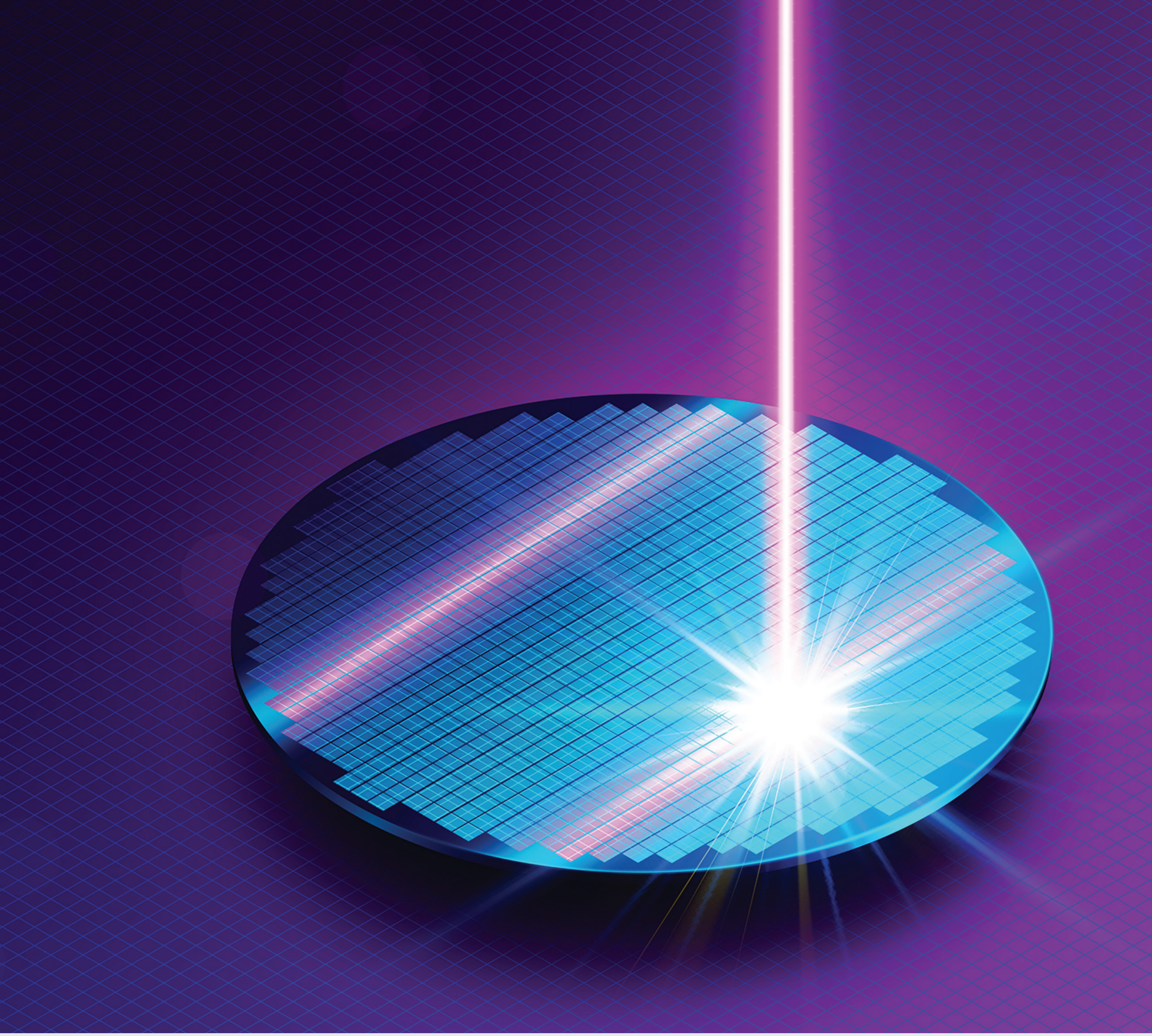


WHITEPAPER

Beyond Precision: Manufacturing and Specifying Superpolished Optics

Superpolished optics minimize scatter, optimize efficiency, and extend the lifetime of precision optics. Those who specify and apply these ultra-refined optics will benefit from some basic knowledge of how they are manufactured, measured, and specified.

"Superpolished" optics is a somewhat relative term. There is no universally accepted threshold that defines when a lens or mirror achieves superpolished quality. The most advanced techniques can achieve sub-angstrom quality. To put that into context, a single hydrogen atom is only 1Å in diameter.

For practical purposes, surface roughness below 3Å RMS exceeds the performance demands required for most precision optics applications. So, optics within 1–3Å arguably qualify as superpolished components able to deliver minimal scatter, optimal efficiency, and excellent wavefront quality. Superpolish techniques also enhance the smoothness of optical coatings, which are directly affected by the roughness of their substrates.

As optical system designers push the boundaries of laser systems, low-loss imaging, and other photonic systems, understanding the manufacturing and metrics of superpolished optics becomes increasingly valuable. Clearer insights into the polishing and measuring techniques for these optics can also help technical buyers to specify them more appropriately for their application and integrate them successfully into high-performance systems.

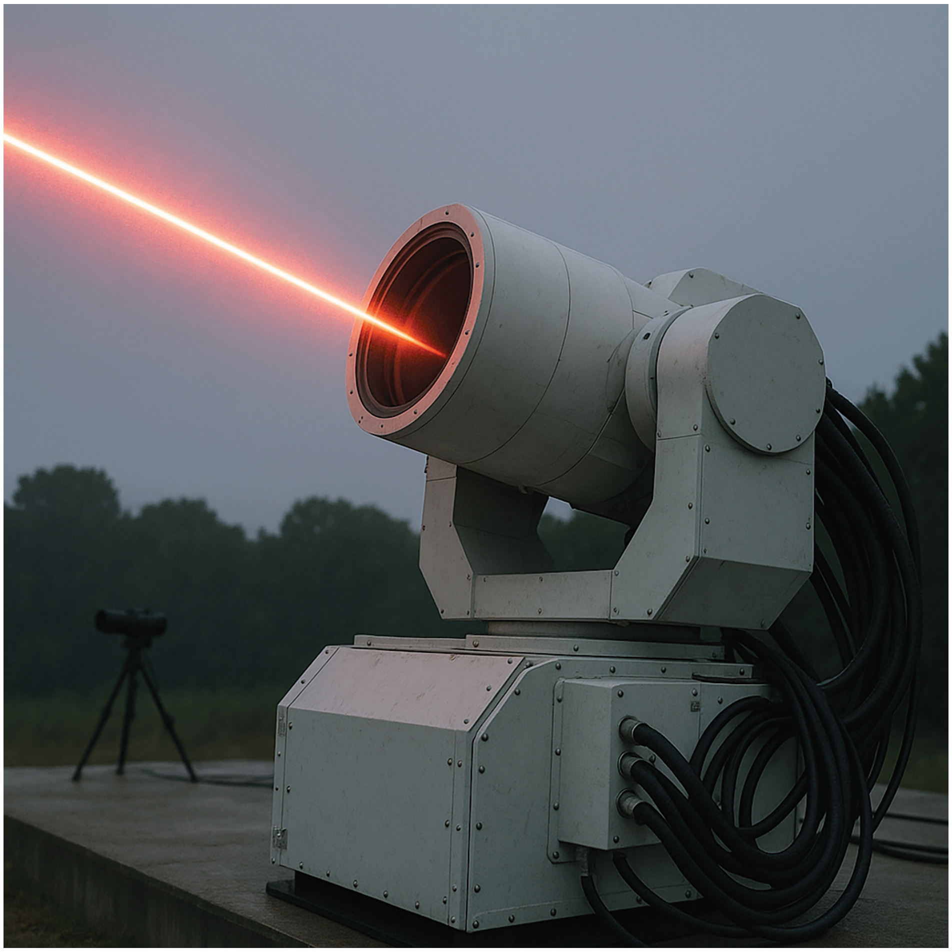
Applications beyond precision optics

Demand for superpolished optics is driven primarily by three application sectors: deep ultraviolet (DUV) semiconductor lithography, ring laser gyroscope navigation systems, and directed energy weapons (DEW). But any application that needs to enhance laser-induced damage threshold (LIDT), extend lifetime, optimize efficiency, or ensure flawless coating deposition will benefit from ultrasmooth optics.

Telescopes, medical imaging tools, and analytical instruments designed to detect very low-light levels, for example, also specify superpolished optics to maximize optical efficiency, signal-to-noise ratio, and image contrast.

Laser systems commonly require superpolished optical surfaces on mirrors and lenses to minimize light scatter, which can reduce laser efficiency, coherence, and lifetime. Scatter

Rayleigh scattering is proportional to the fourth power of the optical frequency of a laser's output. Put simply, scatter is most problematic for lasers emitting short-wavelength light.



Superpolished optics are mission critical for high-power laser systems used in directed energy weapons — not only to optimize output, but also to minimize uncontrolled scatter that can quickly spiral into catastrophic system failure.

can also pose safety risks for laser users, especially in DEW applications where uncontrolled light can quickly spiral into catastrophic system failure.

Scatter increases proportionately with optical surface roughness. Minimizing its impact in laser systems is possible through careful design, by minimizing surface imperfections and contaminants on the laser optics, and with help from anti-reflective coatings. But all of these solutions again rely, in part, on ensuring a laser's mirrors, lenses, and other components are sufficiently polished.

Rayleigh scattering, which is caused by the particles comprising an optical material, is proportional to the fourth power of the optical frequency of a laser's output. Put simply, scatter is most problematic for lasers emitting short-wavelength light. Scatter intensity also scales in nonlinear fashion with particle size, which means that optical surfaces targeting UV applications should be at least an order of magnitude smoother to achieve an equable scatter specification as laser optics targeting visible applications.

Naturally, this applies to the high-frequency lasers emitting DUV light. In addition to reducing the efficiency and intensity of these sources, scatter also limits the tight spatial that DUV lithography systems must achieve to imprint very fine patterns onto a photoresist.

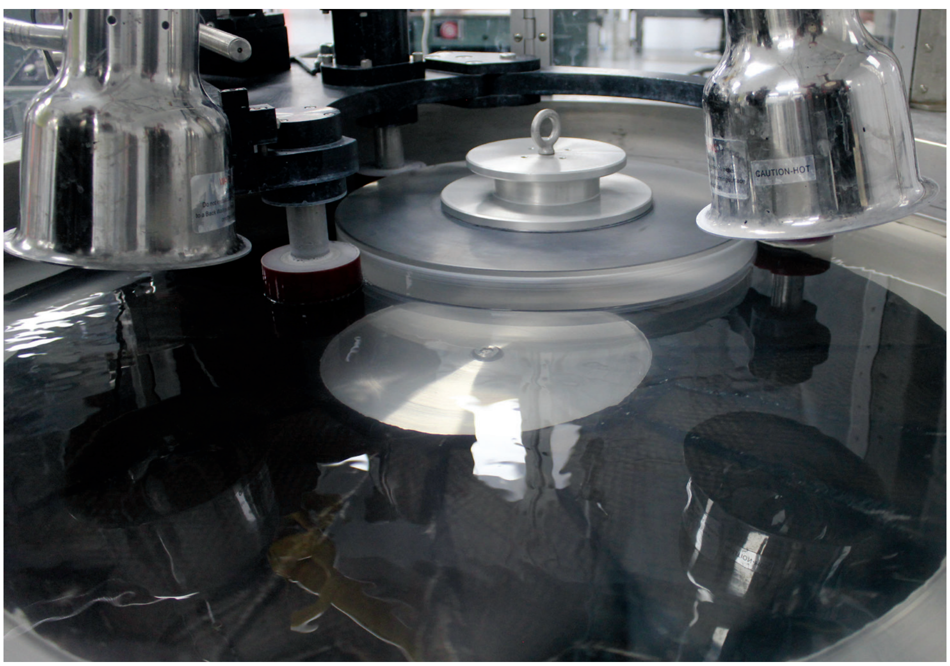
Minor defects on and below an optic's surface can also affect overall system reliability and lifetime. Such defects absorb a portion of the laser's energy and convert it into heat. If sufficiently intense or prolonged, this heat causes localized damage and compounds the defect's impact until the optic surpasses LIDT and becomes ineffective.

Prolonging the reliability and lifetime of optical assemblies, however, is not simply a matter of damage reduction. In some cases, superpolished optics are instrumental to more durable device designs. Such is the case with ring laser gyroscopes used for inertial navigation in aerospace platforms, which typically specify superpolished substrates for the coated mirrors on which these devices rely.

Extending the lifetime of these gyroscopes is less a matter of minimizing LIDT than enabling an inherently more rugged and reliable solid-state alternative to mechanical gyros. Ring laser gyroscopes are effectively HeNe laser cavities configured as a ring. Rotation within the ring's flat plane shifts interference patterns between two counterpropagating cavity modes, which registers as a slight difference in frequency and provides a highly accurate measure of gyro motion.

> The initial polish of a lapped finish, for example, might take roughly 45 minutes to complete and deliver a 20Å surface quality.

Superpolished surfaces ensure the three mirrors forming the laser ring prevent scattered light from transferring from one mode into the other, which would reduce the contrast of the interference fringes and compromise the gyroscope's accuracy. But, importantly, superpolished optics underly the solid-state design that enables ring gyroscopes to perform reliably for the full duration of their 20-year expected lifetime.



Superpolished optics, by definition, pose more stringent manufacturing challenges than conventional precision optics. The initial polish of a lapped finish, for example, might take roughly 45 minutes to complete, whereas achieving a 2Å surface roughness can take hours or days. Due to the specialized nature of these optics and their applications, qualified suppliers typically collaborate closely with users to balance quality, manufacturability, total cost, and end performance for their component.

Mind your materials

Superpolishing can apply to a number of different optical materials, such as fused silica, N-BK7 borosilicate crown glass, calcium fluoride, and Zerodur® glass-ceramic. Each presents different considerations to ensure a high-quality result from superpolishing.

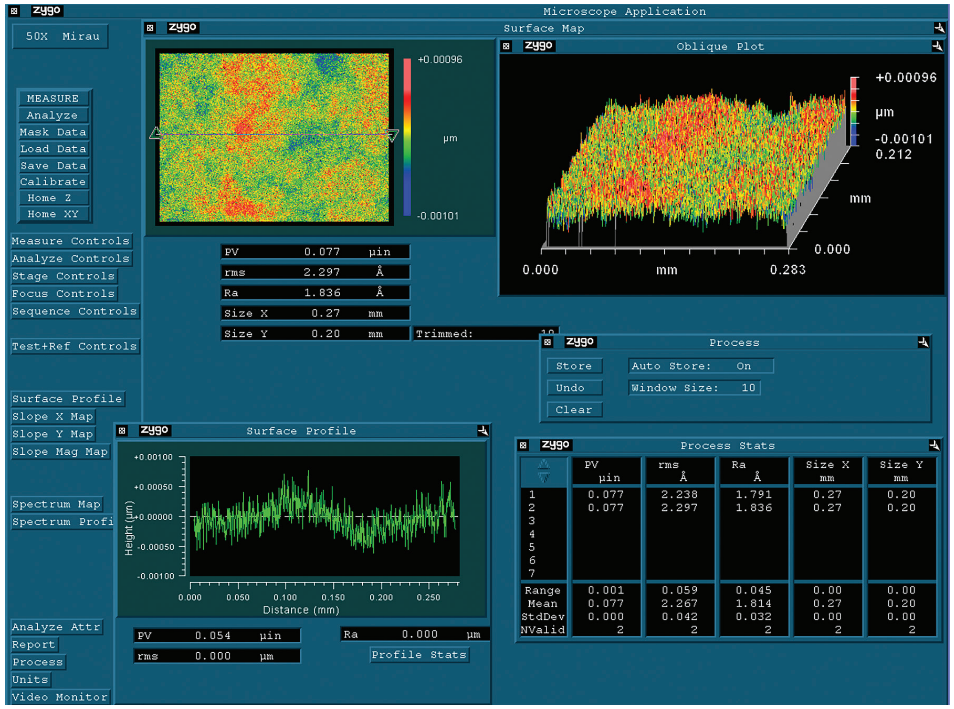
Fused silica expands very little with temperature changes, making it easier to maintain precision during polishing. But temperature control remains important to prevent thermal gradients that can introduce localized stress.

The material's amorphous structure means there are no grain boundaries that can cause scattering, which favors applications that require sub-angstrom surface roughness. Though fused silica's hardness (5.5–6.5 Mohs) requires extended processing times to achieve a superpolished surface, it offers superior surface quality.

N-BK7 offers an excellent balance of optical performance and manufacturability for superpolished applications. Its homogeneous structure delivers consistent superpolishing results, and though the material exhibits moderate expansion during processing, careful thermal management can prevent figure distortion. N-BK7 also has a softer durometer than fused silica, which allows faster material removal rates and reduced processing time. But its low durometer requires precise control of polishing pressures to avoid subsurface damage and edge roll-off.

Zerodur's minimal expansion during polishing makes it suitable for optics targeting thermally demanding applications. The material's two-phase crystalline structure presents unique challenges during superpolishing, as material removal of the glass and ceramic phases progress at different rates. This differential polishing can create micro-textures if not properly managed with specialized slurries selection and process parameters. Zerodur's exceptional dimensional stability virtually eliminates thermal stress concerns during processing. But it is a brittle material that requires attention to approach speeds and careful handling to prevent chipping or fracture during extended superpolishing cycles.

Commonly used in semiconductor lithography applications, calcium fluoride (CaF_2) optics present distinct



The domain of superpolished optics is arguably defined less by current polishing capabilities than by the ability to test and measure surface roughness. Several complementary metrology techniques are required to verify surface quality at specific spatial frequency ranges.

challenges for superpolishing due to its crystalline structure and relatively soft nature (4 Mohs hardness). The material's atomic structure forms a cubic crystal lattice with preferential cleavage planes that can make it hard to achieve a uniform surface finish across different crystallographic orientations. CaF_2 shows moderate expansion during processing, which requires a stable temperature be maintained to ensure figure accuracy. CaF_2 optics also have comparatively high water solubility, necessitating non-aqueous polishing compounds.

Superpolish techniques

The precision and efficiency that superpolished optics afford is helping to drive higher performing photonic systems in multiple end-markets today. This, in turn, is driving fast growing demand and higher-volume production. But superpolished optics, by nature, also push the limits of optical fabrication and measurement methods.

On its surface, so to speak, superpolishing simply extends conventional polishing processes. It begins with a lapped finish and applies a sequence of successively finer polishing steps. Surface roughness is tested between each iterative step and increasingly stringent process controls are applied as the optic progresses. Steps also become progressively longer as the surface approaches sub-angstrom smoothness.

The initial polish of a lapped finish, for example, might take roughly 45 minutes to complete and deliver a 20Å surface quality. Attaining a 2Å surface roughness on the same machine could take on the order of hours or days depending on the scale and sophistication of the polishing operation. Some suppliers claim they can turn around that surface quality in a single day, but the inventory and equipment required can put a premium on such cycle times.

The equipment used is defined by the two most common superpolishing techniques: submerged pitch polishing or magneto-rheological fluid (MRF) polishing.

As its name implies, submerged pitch polishing immerses a pitch tool in polishing compound. This enables conformal contact with the optical surface to help minimize abrasion while maintaining exceptional form accuracy. The process delivers consistent sub-nanometer roughness across large apertures, making it suitable for superpolishing laser mirrors and optics for high-energy applications. The trade-off is that submerged pitch polishing can require cycle times as long as 8 to 12 hours per surface. Tooling costs can also be prohibitive for polishing complex geometries.

MRF polishing offers comparatively faster surface finishing as well as correction of mid-spatial frequency errors. It employs a magnetized fluid ribbon that conforms to complex surfaces and permits more targeted correction of specific surface regions. MRF excels at correcting inherited errors from previous manufacturing steps and can achieve desired surface roughness within 15 to 30 minutes per zone. The technique is effective for aspheric and freeform surfaces where traditional polishing presents challenges.

Selection of either technique depends on surface requirements, geometry constraints, and production economics. In short, submerged pitch polishing delivers superior surface quality, while MRF offers greater efficiency and error correction when polishing complex geometries.

Control is key

No matter how sophisticated the equipment is, achieving the ultra-refined surfaces of superpolished optics requires precise control of multiple interdependent variables throughout the polishing process.

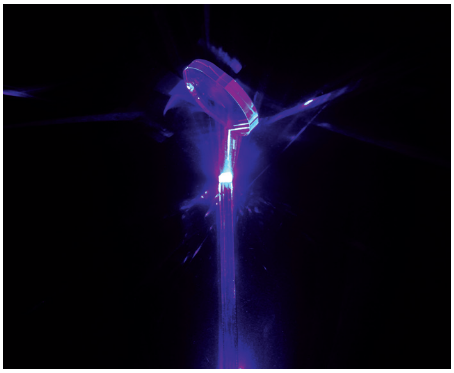
Temperature control within ±0.5°C is essential throughout polishing cycles to prevent

Error Classes for Superpolished Optics

Spatial Frequency (mm-1)	Surface Features Measured	Favored Measurement Tool
Low-spatial frequency (~10-1 to 101)	Large scale deviations in form and shape, such as radius of curvature or parallelism	Conventional interferometry
Mid-spatial frequency (~10-0 to 103)	Surface features typically produced by the manufacturing process, such as machining marks and pits	White-light interferometry (WLI)
High-spatial frequency (~102 to 105)	Smaller scale variations, typically smaller than the wavelength of light used for inspection, such as roughness	Atomic force microscopy (AFM)

thermal expansion of both workpiece and tooling. Any thermal fluctuations introduce form errors and localized stress that manifest as surface irregularities. Maintaining thermal stability also affects slurry viscosity and the formation of the Beilby layer — a controlled chemical reaction at the optical surface that protects the underlying substrate from damage during final polishing stages.

Polishing slurries require extremely high purity to avoid contamination. The suspended grit particles must be softer than the optical material to minimize subsurface damage. Lower concentrations of grit can prolong polishing, while higher concentrations increase the risk of damage. Slurry pH levels above 9.0 optimize chemical-mechanical interactions and prevent particle agglomeration.



The ultrasmooth surfaces of superpolished optics minimize Rayleigh scattering. This is particularly important to optimize the intensity and resolution of the deep-UV laser systems used to fabricate semiconductor chips.

Polishing with mechanical loose abrasives will always incur some damage, especially as an optical surface progresses toward angstrom-scale smoothness. The final stages of superpolish therefore rely on prompting formation of the Beilby layer, which essentially makes the optical material's top layer slightly more fluid compared to the bulk layers below. This layer effectively serves as a barrier that protects the underlying substrate from further damage and contamination during the polishing process. Tightly managing processing conditions allows some control over Beilby layer formation, which enables active engineering of the optical surface to minimize roughness.

Additional attention must be paid to maintaining tool pressure as variations can create surface ripple. Similarly, rotational speeds must maintain consistent relative velocity between tool and workpiece, and isolation of vibration will minimize or eliminate variations in surface texture.

Environmental controls also become increasingly critical as target roughness approaches angstrom levels. When targeting 2Å surface quality, particles larger than 4Å cannot remain on the surface. This necessitates Class 100 cleanroom environments with positive pressure differentials to prevent contamination ingress.

Measurement and verification

In some respects, the domain of superpolished optics is defined less by current polishing capabilities than by the ability to test and measure surface roughness. Polishing and metrology techniques must advance in line with each other.

Verification of surface quality employs three complementary metrology techniques (see table). Each is optimized for specific spatial frequency ranges.

Conventional HeNe laser interferometers measure large-scale figure errors across the entire optical surface. White-light interferometry (WLI) provides more accurate measurement of mid-spatial frequency errors and surface waviness by analyzing interference patterns from broadband reflected light.

For high-spatial frequency measurement of surface roughness, both WLI and atomic force microscopy (AFM) are employed depending on application requirements. WLI's larger field of view enables faster measurement over broader surface areas, making it suitable for in-process testing. AFM directly measures sub-angstrom surfaces; but its small field of view and high sensitivity limit its use to laboratory verification rather than production environments.

Since errors in each spatial frequency category influence overall optical performance, comprehensive measurement across all ranges is necessary. An optic with slightly higher surface roughness might outperform another with a smoother surface if other parameters are better controlled. This interdependence between process control and measurement capability ultimately defines the practical limits of superpolished optics manufacturing.

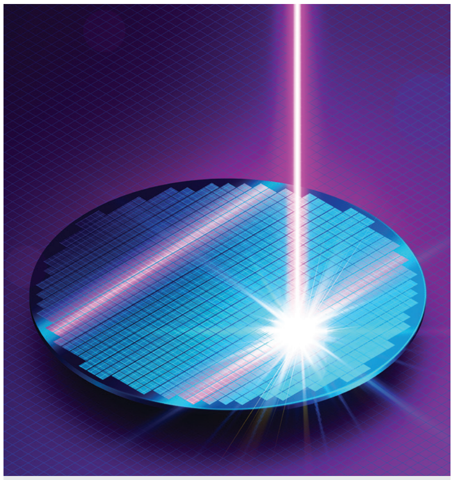
Finding the right superpolished optics supplier

The capabilities of a superpolished optics supplier are defined by more than just the surface roughness they can achieve. Successful application of these optics is also influenced by the supplier's ability to provide specifications, minimize cycle times, and measure quality. Success is further shaped by a supplier's manufacturing environment, production equipment, and measurement tools.

Many optical system integrators develop their own specifications for the precision optics they use. But superpolished optics are by nature defined by unique specifications for a particular application. As tolerances become increasingly stringent, it can be easy for optical specifications and performance demands to be "lost in translation."

It is important to work with superpolished optics providers who can help users design for manufacturability (DFM). Though such support is easy to claim, in practice it requires suppliers to possess significant expertise in a customer's end applications and a proven methodology for collaborating on material selection and design specifications.

Any reputable optical supplier aims to ensure success in a customer's application. The intent of a DFM review, however, is to help customers achieve the optimal balance of total cost, quality, manufacturability, and end performance for their component. DFM reviews become proportionately more valuable as application requirements become stricter, making them mission critical to the success in superpolished optics applications.



As today's precision optics challenge the limits of performance, demand for superpolished optics is rapidly growing. Today's most advanced superpolished optics permit defect sizes that are smaller than the diameter of a single hydrogen atom – or only 1Å.

IRD glass

810 E St Paul St
Litchfield, MN 55355
www.irdglass.com
320-693-7217