Recent advances in high-performance window fabrication

James B. Taylor*, Richard Boland, Edward Gowac, Paul Stupik, Marc Tricard
Zygo Corporation, Laurel Brook Rd., Middlefield, CT 06455

ABSTRACT

The continuous drive towards higher performance intelligence, surveillance and reconnaissance (ISR) and high-energy laser (HEL) systems has translated into new requirements for high-performance windows. In these applications a wide range of materials needs to be considered, ranging from amorphous glass (such as fused silica), polycrystalline materials (such as Cleartran™) or hard ceramics (such as AlON, spinel and sapphire). A wide range of sizes (up to and including meter class optics) and geometries are also considered for these applications (high aspect ratio plano surfaces remain prevalent, of course, but "free-form" shapes are also being envisioned and implemented routinely, including conformal windows). As is always the case, increasingly tighter specifications, driven by lower wavelength IR systems as well as visible and/or multispectral systems, require continually more sophisticated metrology techniques to verify and validate. Development of manufacturing processes needed to yield pristine optical surfaces capable of operating at higher laser fluences and/or for highly brittle ceramics capable of withstanding a wide range of temperature, operating pressure and stress are also considered. New high-durability thin film coatings capable of withstanding increasingly harsher environments have been developed for these applications. In a defense environment where cost pressures continue to require less expensive manufacturing processes, several advances are discussed. This paper will present a wide range of examples dealing with these materials, geometries, specifications, metrology and thin film coating developments.

Keywords: Precision optical fabrication and coating, optical windows, IR windows, sapphire, Cleartran™, spinel, AlON, fused silica, silicon, germanium, metrology, freeform optics, conformal windows, high-energy laser (HEL) windows, intelligence, surveillance and reconnaissance (ISR) windows

1. INTRODUCTION

Zygo Corporation is well-known as a provider of industry-standard metrology for a variety of applications, including interferometrically based instruments for measuring surfaces at both a macroscopic and microscopic level. In addition to providing optics and reference surfaces for its own instruments, Zygo's Optical Systems Division also manufactures and sells a variety of optics to outside customers in the laser fusion (e.g. HEL), defense (e.g. ISR), biomedical (e.g. opthalmic laser surgery lens assemblies) and semi-conductor markets (e.g. lithography) through manufacturing sites in Middlefield, CT, Richmond, CA, Costa Mesa, CA and Tucson, AZ. Zygo is well-known for making large, high-quality plano optics, but also has world-class expertise in the fabrication of aspheres, free-form and conformal optics as well as glass and glass-ceramic structures. Zygo has developed a variety of technologies for making and measuring some of the most difficult and high-quality optics in the world. The results of some of these developments will be shared to illustrate the current state of the art and recent advances in the production of high-performance windows.

2. HIGH-PERFORMANCE APPLICATIONS

2.1 Laser fusion / high-energy lasers

For more than a decade, Zygo Corporation has been manufacturing meter-class optics for laser fusion and high-energy laser applications. Zygo has fabricated in excess of 5,000 optical amplifier slabs for HEL applications throughout the world.

*jtaylor@zygo.com; phone: 1.860.347.8506; fax: 1.860.347.8372; www.zygo.com

Figure 1. Cladded HEL optical amplifier slab.

Zygo also fabricates meter-class mirrors, grating substrates, continuous phase plates and other optics for HEL applications, but the fabrication of so-called 3ω optics is by far the most challenging. Optics classified as 3ω are subject to high fluences that would literally destroy most optics processed with standard manufacturing approaches [1]. In addition to exacting Laser Induced Damaged Threshold (LIDT) specifications 3ω optics include very tight figure requirements on a meter-class optic, as well as slope specifications, surface quality and sub-surface quality of the optics.

The use of transmissive optics in the 3ω portion of a HEL beam line (after the frequency has been tripled from 1.053um to 351nm, just before the target) has presented a significant challenge to all those who have attempted to manufacture such optics. In addition to the exacting optical characteristics desired to maintain the shape of the pulse, the optics must also have the ability to withstand very high fluences. The presence of any surface or subsurface defect greatly reduces the ability of an optic to withstand high laser fluences and thus special processes have been developed to ensure an appropriate quality for all 3ω optics. At Zygo, the 3ω process consists of a variety of full aperture polishing processes followed by subaperture polishing processes with both intermediate and final etching steps to reveal any surface or subsurface damage. Proper use of these processes has yielded transmissive optics that can withstand as much as $15J/cm^2$ fluence over a 400mm X 400mm aperture.

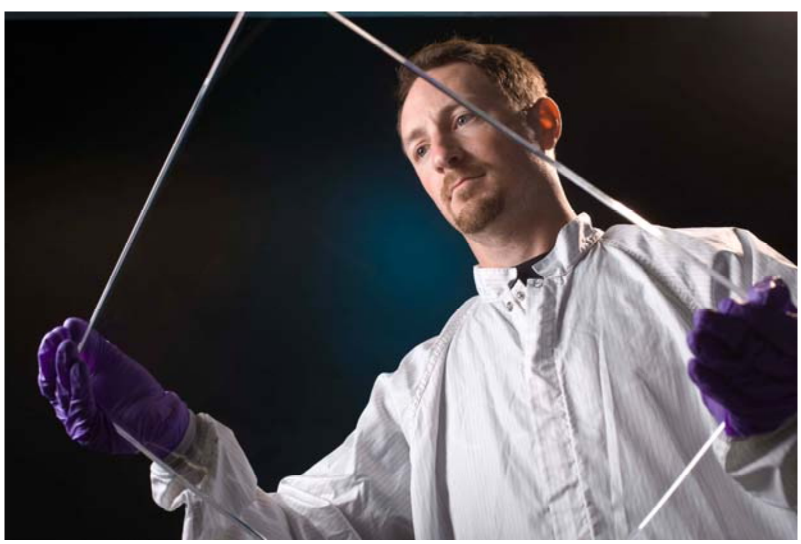

Figure 2. 3ω HEL transmissive optic.

2.2 Intelligence, surveillance and reconnaissance (ISR)

Windows for ISR applications have received a significant amount of attention and development with the advent of Unmanned Aerial Vehicles (UAV) and other remote sensing techniques for keeping an eye on various activities. A significant proportion of these techniques incorporate either infrared (IR) or multispectral sensors that have been tasked to gather information with extraordinary precision and resolution. Most multispectral window materials are notoriously difficult to manufacture as well as being very expensive, especially as performance and breadth of coverage are improved. Another major issue in ISR is the fact that the optics are typically in very challenging environments that can expose them to extremes in weather, temperature, humidity, particulates, etc. Zygo Corporation is a leader in the manufacture of ISR windows for land, air, sea and space applications [2]. These windows operate in a wide range of environment ranging from undersea application to high altitude, over a wide range of temperature and pressures, not to mention aggressive environmental extremes. As with windows in HEL applications, controlling surface defects is therefore a key to superior performance. Zygo has developed advanced processes for qualifying ISR window materials, some of which have significant birefringence to ensure that the ultimate performance will be within specifications before investing significantly in manufacturing the component windows. Additionally Zygo has developed several proprietary polishing processes for ISR materials, including Cleartran™ [3] and sapphire [4, 5].

3. MATERIALS AND SIZE

3.1 Amorphous materials:

Zygo continues to manufacture a significant number of high-performance windows from traditional glasses such as n-BK7 and fused silica. One of the more interesting applications for such transmissive optics is in very large formats as windows and transmission flats for interferometric applications. Zygo routinely manufactures transmission flats for its own instruments in 24" and 32" formats with reference surfaces as good as λ/20 P-V. Zygo has also recently produced aircraft observation windows in excess of 1.25m in diameter to very exacting specifications. This application was the first instance that Zygo used stitching algorithms on a 32" interferometer.

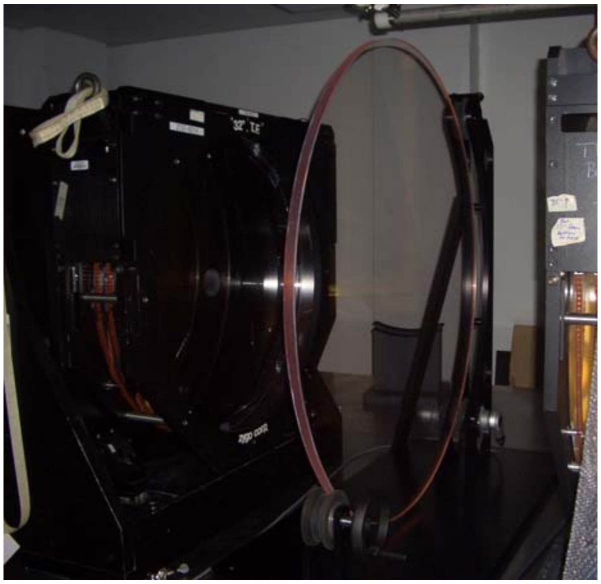

Figure 3. 50" dome window in a 32" Zygo wavelength shifting interferometer.

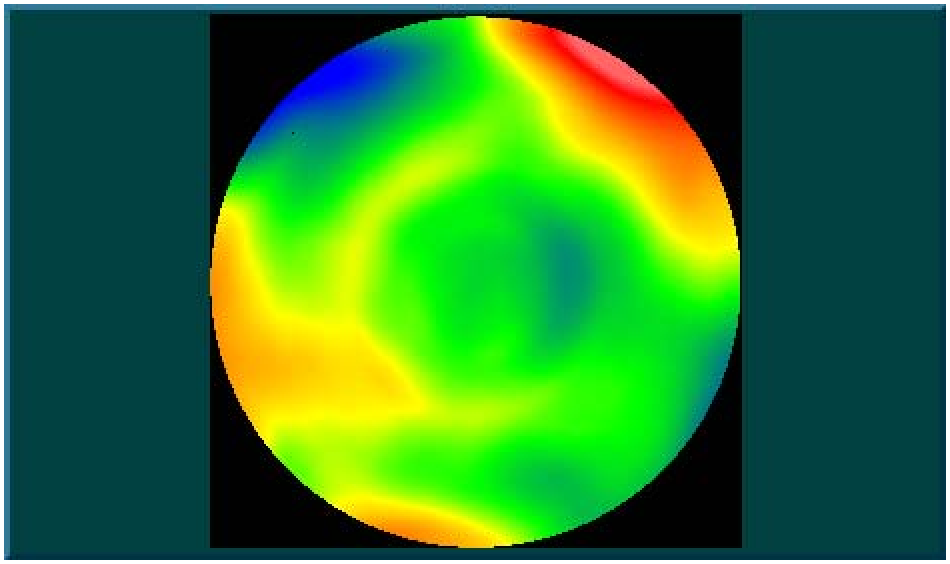

Figure 4. Stitched interferogram of 50” dome window showing 0.25 waves RMS.

3.2 Cleartran™

Multispectral ISR applications often call for the use of ZnS because of its transmissive properties at various wavelengths of interest. Cleartran™ is a commercially available version of ZnS that has excellent optical properties, but which is very difficult to manufacture, particularly during polishing. Zygo has invested significant time and effort in developing grinding and polishing processes that allow high-performance ISR windows to be manufactured out of Cleartran™ in an economical way while meeting both the optical and cosmetic requirements for the application. The low fracture toughness and other mechanical properties of this material make it particularly susceptible to chips, edge flakes and issues with scratches and digs. Using proprietary hybrid techniques and specially formulated polishing compounds has allowed Zygo to offer high-performance, large format windows made of this very special material. Zygo routinely makes windows in excess of 300mm using Cleartran™. One crucial technology developed by Zygo is Multi Surface Technology (MST, [6]) that allows for the simultaneous measurement of the front surface, the back surface, the transmitted wavefront and material homogeneity of thin parallel optics.

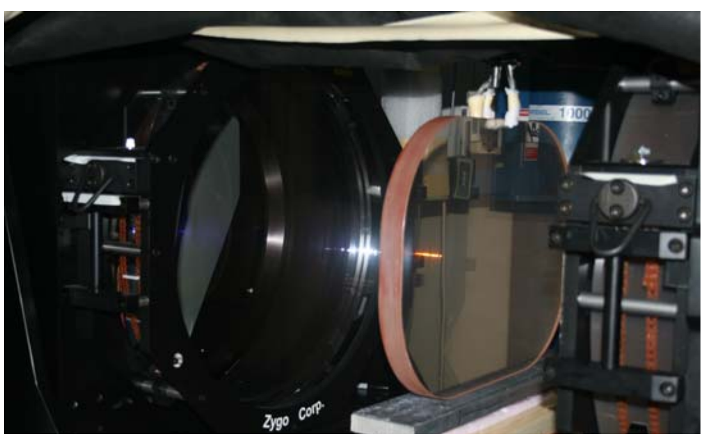

Figure 5. Cleartran™ window in a 24” Zygo MST Interferometer.

3.3 Sapphire

When the mechanical integrity of a window is paramount, the choice for ISR windows can often be sapphire. As a single crystal material with a Knoop hardness in excess of 2,000, anisotropic properties, high strength and low fracture toughness, sapphire poses a variety of challenges in manufacturing. Zygo has made a large number of sapphire windows that have application in extreme environments, including high pressure and submerged under water. Zygo has developed a double-sided polishing process for these applications that makes for a relatively economical solution. Adding a high quality edge and bevel polish for absolute mechanical integrity is one of the findings of the SSCARR program, of which Zygo was a participant [7]. Participation in this and similar programs, a continual focus on development and the ability to perform sophisticated analyses are areas that set Zygo manufacturing apart.

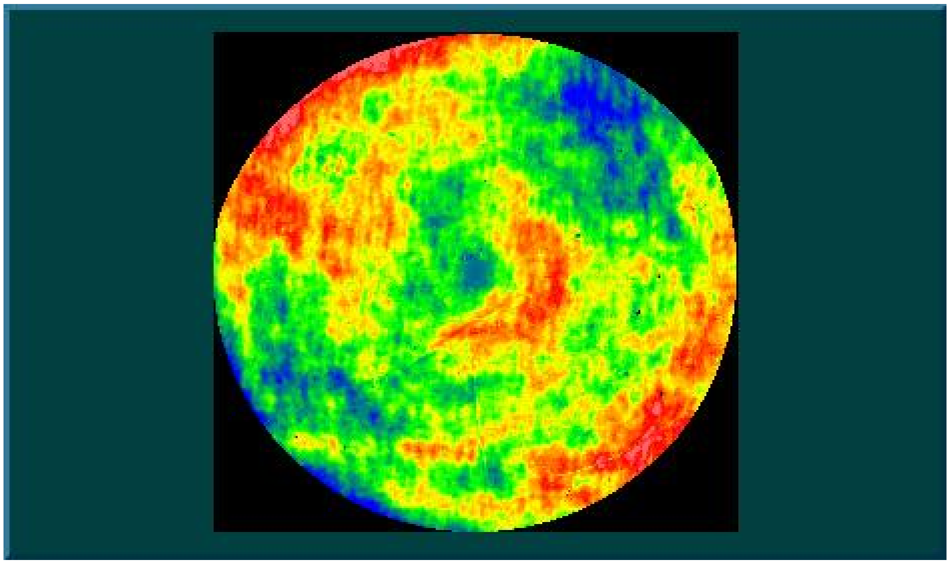

Figure 6. 170mm flat with 2.6nm RMS transmitted wavefront error.

Figure 7. Sapphire window.

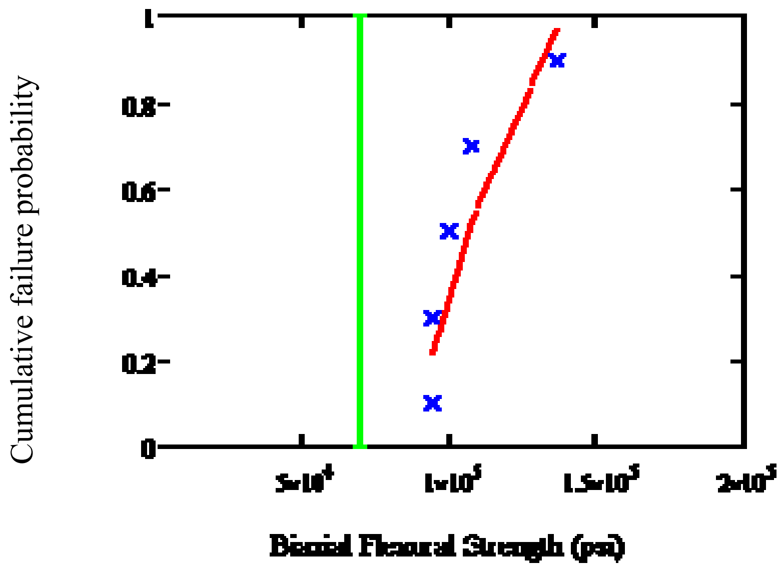

Figure 8. Mechanical property analysis based on as processed conditions

4. GEOMETRIES

4.1 Aspect ratio

One of the most difficult problems in optical manufacturing is understanding how optics change shape under various loading conditions such as gravity, differential pressure, coating induced stresses and mounting stresses. These issues are extraordinarily difficult to understand and compensate for when the aspect ratio of the optic is severe. Typically Zygo prefers to design high-performance optics with a length to thickness ratio of no more that 6:1 to minimize the aforementioned effects, but will often be forced to accept ratios of 10:1 or more based on design constraints. On occasion Zygo has been asked to manufacture optics that have an aspect ratio of more than 100:1 which require very specialized blocking and compensation techniques to meet any optical specifications. Zygo currently manufactures a variety of meter class optics with aspect ratios of more than 300:1 using these techniques.

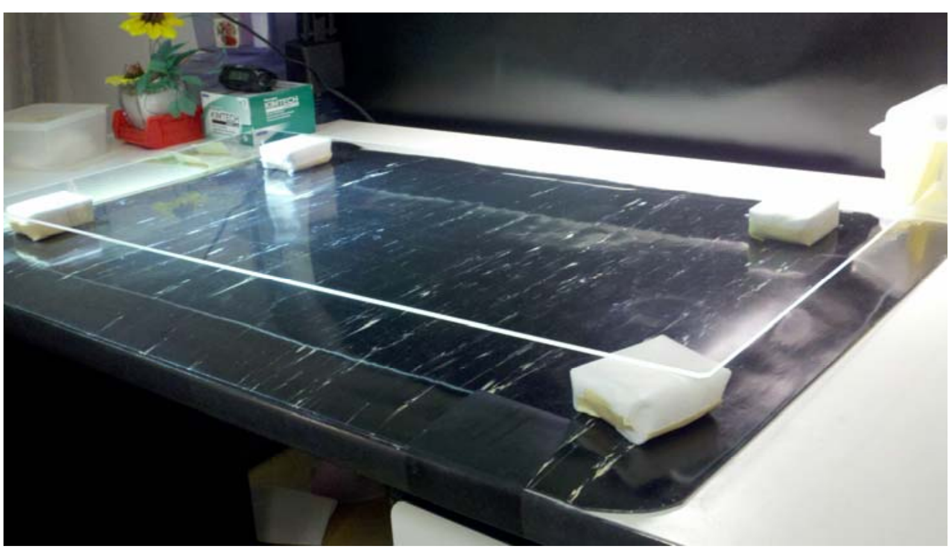

Figure 9. Optic with greater than 200:1 aspect ratio.

4.2 Freeform

Zygo has recently been producing a specialized optical component that has both reflective and transmissive requirements, is freeform and has an aspect ratio in excess of 60:1. One of the most challenging problems presented by this optic was the need for a final product with unequal coating stresses on either side. The resultant deformation caused by the coating stresses was several microns of departure from specification. Zygo developed an analysis and predictive technique that allowed for the optic to be manufactured to process specifications that took the subsequent coating deformation into account. The result was an optic that was only in specification after the coatings were applied and the resultant deformation pulled the optic into the proper final shape.

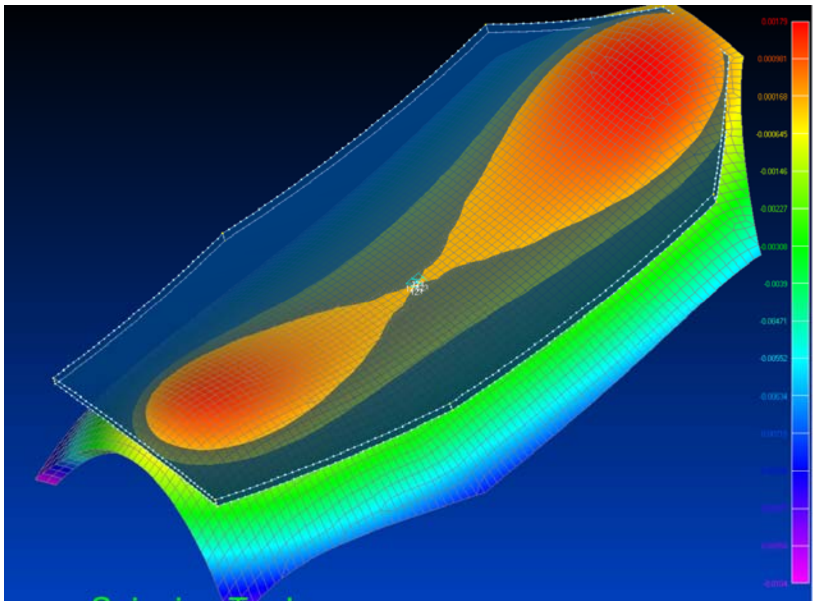

Figure 10. Finite element model of coating induced deformation in a freeform transmissive optic.

5. COATINGS

5.1 Performance

Optical thin film coatings are the crucial technology that allows optics to become high-performance windows and meet required transmission specifications. Zygo has been producing windows designed for a large variety of wavelengths, with, of course, the more technically challenging optics needing to meet very broad wavelength coverage, resistance to degradation from high fluences, and/or the ability to withstand extreme environmental exposure. Zygo makes use of the full gamut of coating technologies to meet the needs of its customers and their various optical designs, with coating chambers up to as large as 72" inches. Providing coatings from the UV to the IR, Zygo can also provide a comprehensive suite of environmental testing services.

5.2 Laser fluence

Zygo has been able to provide a variety of coatings for laser applications. Many of these applications include requirements for maintaining the integrity of the coating under significant laser fluences. Zygo has recently provided coatings that have performed to specification at fluences in excess of 4 J/cm^2.

5.3 Environmental resistance

Coatings for aerial reconnaissance windows typically have stringent durability requirements including temperature, humidity, salt fog, blowing dust, etc. Meeting these requirements has proven to be difficult in many applications, not only because of the durability of the coatings themselves, but because the mechanochemical properties of the substrate itself. Many of the IR materials are particularly prone to various failures that initially manifest as coating durability failures, but which are in reality mostly related to the properties of the substrate. ZnS is a good example of a multispectral window material that is notoriously difficult to coat in a manner that provides a reasonably durable coating. Work at Zygo has shown that many ZnS coating failures are actually attributable to the substrate and its mechanical and chemical properties. Zygo has recently developed a ZnS coating for multispectral applications that is durable in extreme environmental conditions and which is flight worthy for ISR applications.

Figure 11. Witness samples of ZnS coatings, sample on left showing degradation after extreme environmental exposure and the sample on the right showing no degradation after extreme environmental exposure.

REFERENCES

[1] Menapace, J.A., Penetrante, B., Golini, D., Slomba, A., Miller, P.E., Parham, T., Nichols, M. and Peterson, J., "Combined advanced finishing and UV-laser conditioning for producing UV-damage-resistant fused silica optics," Proc SPIE 4679, 56-68, (2002).

[2] Hachkowski, R., "Getting it right with high-performance ISR Windows", Photonics Spectra, August 2009.

[3] Harris, D.C., "Development of hot-pressed and chemical-vapor-deposited zinc sulfide and zinc Selenide in the United States for optical windows," Proc SPIE 6545, 02-1 to 27, (2007).

[4] Harris, D.C., " A century of sapphire crystal growth," Proc. 10th DoD Electromagnetic Windows Symposium, 1-17, (2004)

[5] Harris, D.C., "Material for infrared windows and domes, properties and performance," SPIE optical engineering press, Bellingham, WA, (1999).

[6] See http://www.zygo.com/?/met/interferometers/verifire/mst/

[7] McClure, D., Cayse, R., "Sapphire statistical characterization and risk reduction (SSCARR) program for windows and domes," Proc. IRIS materials, MIT, (1999).