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Optical Design Capabilities at Lawrence Livermore National Laboratory

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Optical Design Capabilities at Lawrence Livermore National Laboratory

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Summary

Optical design capabilities continue to play the same strong role at Lawrence Livermore National Laboratory (LLNL) that they have played in the past. From defense applications to the solid-state laser programs to the Atomic Vapor Laser Isotope Separation (AVLIS), members of the optical design group played critical roles in producing effective system designs and are actively continuing this tradition. This talk will explain the role optical design plays at LLNL, outline current capabilities and summarize a few activities in which the optical design team has been recently participating.

Lens design – a working definition of the field

In order to explain the role of optical design in optical engineering, let me clearly state what optical design means in this context. In the design of an optical system, many aspects come together – optical, mechanical, and electronic to name an obvious few. Lens design is the craft of specifying the optical components in order to optimize optical performance in the presence of requirements established at least in part by the mechanical and electronic limitations of the system. An additional aspect of this optimization normally includes minimizing cost, assuring manufacturability of the optical components and optical design robustness to assembly and alignment tolerances. While a talented optical engineer can handle design issues spanning optical, mechanical, and electronic aspects and take the complete design "cradle to grave", the addition of a lens designer to the design team can radically improve overall performance and ease of use, while sometimes reducing cost as well. The lens designer is also skilled at recognizing physically unrealizable requirements for optical systems. These talents have kept the demand for lens design steady across decades.

Role of optical design in optical engineering

While it is true the optical engineering has seen an explosion of interest in the last ten years, this growth has not necessarily occurred within the optical design arena. Photonics – not even a word a few years ago - has evolved into a field that has been a new hot source of research and interest, as has nano-optics, adaptive optics, and diffractive optics. While similar innovations have occurred in optical design, the perception remains that the field has been unchanged since the time of Galileo. As a result, universities have been producing a steady stream of optical engineers geared to meet demands in the telecommunication and photonics industries, and, in general, have not emphasized lens design. Only two universities nationwide have the strong reputation for producing lens design graduates and, in one case, there has been a demonstrated difficulty in keeping staff on board to continue this tradition. So the few lens design graduates available are usually heavily recruited by industry.

A contributing factor that masks the urgency of this problem is the steady improvement and innovation of optical design software. Optical design was once considered a task so subtle that only the best trained should attempt it. W.T. Plummer noted the difficulty present in early optical design efforts by stating that "Confronted with a lens design problem, a few men with a genius or a knack could sense the direction to take. Then it was a matter of the laborious application of Snell's law over and over again as designs were checked out by tracing the paths that rays of light might take from the object to the image. Few outside the profession could comprehend the magnitude of the task ... The key to a successful outcome was persistence."[1] In marked contrast, the relative ease of use of the design optimization features in current optical design software and the incredible increase in computational speed and memory capacity of modern computers leads optical design neophytes to the mistaken belief that anyone can design an optical system. As with any tool, the product remains only as good as the user. It requires a trained eye to spot poor design forms and optimization "solutions" that are problematic to implement or unnecessarily costly to build. For example, design of an optical relay system with a wide field of view can lead to large costly optics, while the addition of a field lens can keep performance and budget manageable. Some optimization techniques will lead to compensated errors being introduced to the system design, complicating element fabrication unnecessarily and again driving up cost. Even more serious to the welfare of a project is that fact that these aspects sometimes only become apparent relatively late in the project, after a design on paper is actively being translated into glass and metal.

LLNL has been historically been fortunate to have excellent lens designers on staff and recognizes their value to the organization. A few years ago, we lost a substantial fraction of our lens design talent to the "boom" in the telecom market. We have worked to rebuild a team that in some ways is even stronger than before. The current team possesses a diversity of talents and backgrounds and works as an effective optical design group.

Overview of the Optical Design Group

The optical design team currently resides within Engineering Directorate in the Laser Science Engineering Division (LSED). We are composed of nine staff optical engineers and three contract optical engineers. For the staff engineers, the cumulative experience exceeds 177 years of technical experience with the average experience being almost 20 years since B.S. The diversity of the group not only encompasses a variety of fields of expertise, but is also apparent in the variety of career paths present. Roughly a third of the group has an extensive history at LLNL, while the remainder has an assortment of backgrounds in industry, aerospace and university experience. This range of perspectives has proven very valuable in cross-pollinating designs by one engineer with concepts and techniques provided by another.

As mentioned above, the group possesses a range of fields of expertise that includes a strong emphasis on lens design for imaging systems as well as other optical design fields that might typically be present in a group that provides broad optical design support. We have several engineers knowledgeable in various stray light analyses and IR designs for defense applications while others excel in spectrometer design. Based on our close involvement in LLNL metrology efforts, we have an excellent capability for testing and analysis in support of fabrication. In fact, we recently sponsored a particularly innovative metrology effort at the University of Arizona, Optical Science Center[2] to characterize the back focal length of extremely long focal length lenses to two parts in 10^4. In support of the LLNL laser program, we have also developed an expertise in optical specification techniques, wavefront specifications in particular.

While just the breadth of these fields of expertise is an accomplishment, we possess unique capabilities as well. Our understanding of high-power laser design, including aspects that effect optical damage risks and techniques such as relay imaging to control irradiance distributions, is equaled in only a few places in the world. Our understanding of optical specifications using the power spectral density function is also unique, particularly in regards to its role in optical system performance. We are well on our way to building a strong capability at novel, compact spectrometer design in support of hyperspectral imaging. We are also developing novel design optimization routines that can be extended to the design of grazing incident, x-ray optics – a regime where current optical design software products are poorly behaved.

We have inadvertently developed a "science policy" expertise within our group with one member having a degree in the area and another with NATO experience. We have yet to see how this particular capability will steer the optical designs.

Current and recent projects

While the charter of the Laser Science Engineering Division is largely to support the National Ignition Facility (NIF) Programs, the optical design group's customers span the whole of the laboratory and encompass projects outside LLNL as well. Over the past few years, our major customer has been the NIF project, with the staff producing the optical design for the laser and supporting diagnostic systems. Each of these systems has now been fielded with success. We have also been responsible for the optics specifications and drawings required for procurement. As initial installation has progressed, we have also played an important role in the disposition of non-compliant optics.

We also support the NIF Programs through design support to the Laser Science and Technology Programs. We have designed the optical layout and provided optical design analyses for laser systems such as Mercury and Phoenix as well as made improvements in the Diffractive Optics Manufacturing capability.

For the Mercury laser, a laser designed to serve as a prototype for inertial fusion energy laser systems, our group has designed the general optical layout and is completing a thorough stray light analysis which includes ghost analysis and pencil beam analysis. While ghosts are a common term for any optical surface reflection other than that of the nominal optical path, pencil beams are a particular category of ghost that are created by

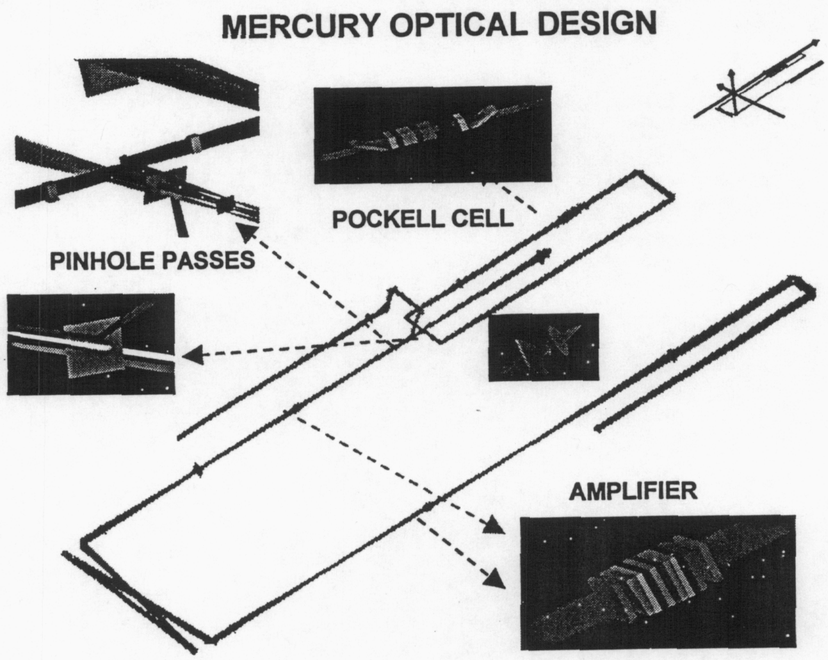

Figure 1. Optical model of Mercury laser system showing multiple pass configuration.

backlighting the pinhole of a spatial filter (i.e., an afocal telescope with a pinhole which effectively limits spatial frequencies which can be transmitted). Since the backlit pinhole is at the focal point of the lens, the light exiting the telescope will be collimated and trace the nominal path of the laser and often encounter laser gain media. This "manifestation of the gut ray" can be a mechanism for optic damage in high-power laser systems.

We also have contributed to Phoenix, the laser optical damage test and conditioning system by redesigning the optical layout to incorporate relay imaging to reduce the effects of beam jitter and to improve control of the beam spatial shape. We developed a system to produce stable, "flat-top" beam footprints on the sample, and formulated a simple plan for allowing the fluence to be selected. The irradiance exiting the laser has a

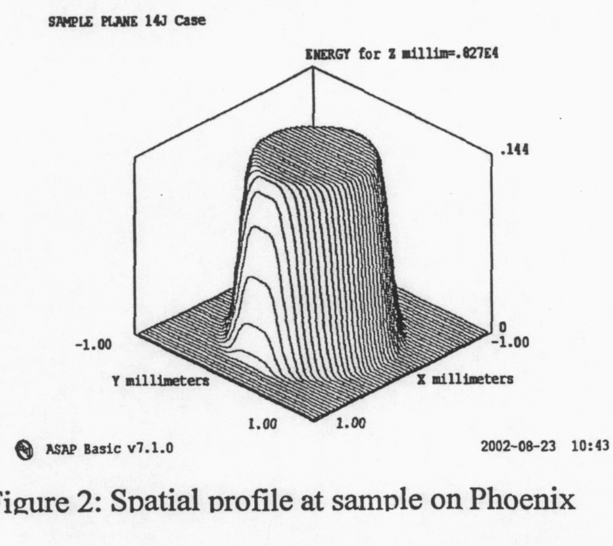

Figure 2: Spatial profile at sample on Phoenix

uniform spatial distribution that quickly becomes a gaussian distribution as the beam propagates. The gaussian spatial profile was not desirable for sample illumination. In order to produce a flat spatial distribution at the sample plane, we redesigned the optical system form a relay image of the laser output at the sample, resulting in enhanced scanning speed and minimizing beam jitter. The fluence level of the energy distribution is controlled by small movements of the imaging lenses to change the diameter of the beam profile while maintaining the relay condition. Off-the shelf optics were chosen to allow the energy distribution to be scanned from 14J down to 2J at the sample and the full range of the design was accomplished with 2 sets of zooming lenses.

Our support has also included work for the Physics and Applied Technologies Directorate. For this group, we have provided optical design support of projection systems for extreme UV lithography, contributed on the early work with the Laser Guide Star and are currently working on designing an off-axis parabola for the compact temporal pulse compression system for the Petawatt Laser program.

We have recent begun work in support of the Nonproliferation, Arms Control and International Security (NIA) Directorate. We have redesigned existing Large Area Search Initiative (LASI) spectrometer designs for ease of fabrication and assembly and are currently working on novel, new design concepts that reduce device size while maintaining excellent spatial and spectral quality.

Members of the group have also been active in the astronomical telescope design community. In particular, we have been active in the evolution of the optical design of the Large Synoptic Survey Telescope (LSST), presenting an improved optical design for the telescope.[3] The LSST is a proposed f/1.25 three-mirror telescope covering 3.0 degrees full field angle, with 6.9 m effective aperture diameter and operating at five wavelength bands spanning 386.5 nm to 1040 nm (B, V, R, I and Z). For all bands, 80% of the polychromatic diffracted energy is collected within 0.20 arcseconds diameter. The reflective telescope uses an 8.4 m f/1.06 concave primary, a

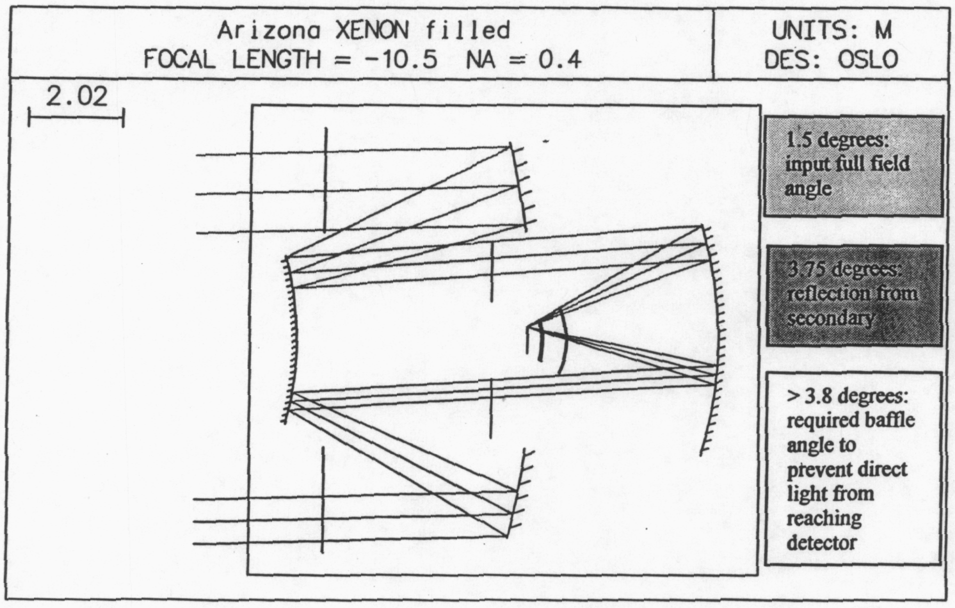

Figure 3. LSST design modification proposed by LSED Optical Design Group member

3.4 m convex secondary and a 5.2 m concave tertiary in a Paul geometry with a system length of 9.2 m. Earlier designs required that one element be a vacuum barrier, but now the detector sits in an inert gas at ambient pressure, with the last lens serving as the gas barrier. Small adjustments lead to optimal correction at each band. Each filter has a different axial thickness, and the primary and tertiary mirrors are repositioned for each wavelength band. Features that simplify manufacturing include a flat detector, a far less aspheric convex secondary (10 μm from best fit sphere) and reduced aspheric departures on the lenses and tertiary mirror. Five aspheric surfaces, on all three mirrors and on two lenses, are used. The primary is nearly parabolic. The telescope is fully baffled so that no specularly reflected light from any field angle, inside or outside of the full field angle of 3.0 degrees, can reach the detector.

As an aside, work by members of our team in support of metrology on the large segmented primary of the California Extremely Large Telescope is currently dormant, awaiting a new surge of interest and funding.

Summary

Among the many optical engineers working at LLNL, a distinct group exists which specializes in optical design issues. The optical design group collectively has a wide range of fields of expertise as well as a diversity of background histories including LLNL, university, industry and aerospace experience. This unique resource has resulted many effective and productive designs for customers at LLNL and outside the lab.

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[1] W.T. Plummer, J. G. Baker, J. V. Tassell, "Photographic optical systems with nonrotational aspheric surfaces," Appl. Opt. 38, 16 (1999).

[2] Brian DeBoo and Jose Sasian, "Novel method for precise focal length measurement", Proceedings from International Optical Design Conference, June 3-5, 2002 Tucson, AZ, to be published.

[3] L. G. Seppala, "Improved Optical Design for the Large Synoptic Survey Telescope," Proc. SPIE 4836-19 (2002).