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OPTICAL ENGINEERING PROBLEMS ASSOCIATED WITH CONSTRUCTION OF THE SHIVA LASER FUSION FACILITY*

R. O. Godwin, E. S. Bliss, J. A. Glaze, W. C. O'Neal,
H. G. Patton, M. A. Summers, E. P. Wallerstein
University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, California 94550

Abstract

The Shiva laser system is part of a new 20 terawatt laser facility at Lawrence Livermore Laboratory. The system contains more than \$5,000,000 worth of optics. This paper discusses the various optical components, typical component quantities and specification, and the problem of laser damage to components.

Introduction

The Shiva laser is a twenty-arm Nd:glass laser fusion facility which is in the final phases of system activation. Figure 1 is a model of this laser system. This system has been described extensively from both an engineering and physics viewpoint^(1,2,3,4,5); however, this paper will address some of the unique optical problems associated with a project of this size. The Shiva laser has been designed to focus more than 20 terawatts (2×10^{13} W) of laser power onto a fusion target a few hundred microns in diameter. To achieve this power level requires twenty identical laser chains, each with an input aperture of 2.5 cm diameter and a final output aperture of 20 cm diameter.

Figure 1
Model of Shiva laser showing laser chains and capacitor banks.

The entire laser systems contain more than \$5,000,000 worth of optical components of varying sizes, types, and configurations. This paper will discuss the various types of optical components used, typical specifications and quantities of optics, and the problem of the laser damaging optical components.

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Optical Components

Several different optical materials are used in large solid-state fusion lasers. These include passive materials for lenses, windows, and polarizer substrates, and active materials for the lasing medium, Pockels cells, and Faraday rotators. Glasses have been used for these applications because of the requirements of high optical quality and large sizes (beam apertures of 20 cm). Crystalline materials are used for components such as the oscillator rod, Pockels cell shutters, and Pockels cell switchouts.

Intense laser pulses change the refractive index of the optical material they pass through--both optical glass and laser glass--by an amount that varies with the pulse intensity. This effect which leads to beam breakup and loss of focusable energy limits the performance of high-power lasers. Therefore, of the many properties entering in the selection of optical materials, the nonlinear refractive index is of prime importance.

For the lasing medium, one is also concerned with several spectroscopic parameters, including wavelengths and intensities of absorption and emission bands, excited-state lifetimes and quantum efficiencies. Requirements on optical quality of transmitting dielectric materials include refractive-index homogeneity (about 10^{-6}), low birefringence (lower than about 5 nm/cm), no absorption at the laser wavelength, and no bubbles, striae, or metallic inclusions. Other physical and chemical properties of interest are the hardness and capability for optical finishing to about $1/20$ of a wave, the stability of the material, and environmental durability. The laser material is exposed to and heated by intense xenon-flashlamp radiation. Therefore thermal properties such as expansion, conductivity, change of refractive index with temperature, stress-optic coefficient, and solarization are also factors.

Finally, the selection of optical materials is also governed by their costs, since there may be alternate approaches, such as larger magnetic fields for Faraday rotators, to increasing output power. Optical materials are a large (but not dominant) cost of large laser systems.

The Shiva laser uses commercial silicate-based laser glasses. These glasses were not developed for use in today's high power laser systems; however, they were readily available and represented a low technical risk for construction of the Shiva laser. Table 1 gives the volume of glass used, Table 2 gives the glass surface area that required finishing, and Table 3 gives the surface area that required thin film coatings.

Table 1. Volume of Glass

	Shiva
Laser Glass	400 liters
Transmitting substrates, flat	92 liters
Faraday rotators	12 liters
Mirrors	240 liters
Lenses	48 liters
Total	792 liters

Table 2. Area of Glass

Laser glass	35 m ²
Transmitting substrates, flat	14 m ²
Faraday rotators	2 m ²
Mirrors	56 m ²
Total flatwork	56 m ²
Lenses	7 m ²
Total	63 m ²

Table 3. Area of Thin Film Coating

Antireflection coatings	13 m ²
Polarizers	5 m ²
Mirror coatings	5 m ²
Total	23 m ²

All large laser systems, such as Shiva, require optical isolation to prevent reflected, scattered, or transmitted laser radiation from being propagated back down a large chain and damaging the optical components. This optical isolation is obtained using the Faraday effect. A Faraday rotator disk is placed between two polarizers oriented at 45°, and a magnetic field is applied to rotate the plane of polarization of light transversing the disk by 45°. Forward-going light then passes through the second polarizer and onto the target; however, back-reflected light undergoes an additional 45° rotation and is rejected by the first polarizer.

The requirements for a good Faraday rotator material include low absorption at the laser wavelength, low birefringence, high homogeneity, and high threshold of damage. The angle of rotation of the polarization is given by $\theta = V\lambda H$, where V is the Verdet constant, λ the interaction length, and H the component of the magnetic field in the direction of light propagation. For a 45° rotation in a given H field, the Verdet constant of the material should be as large as possible to reduce the optical pathlength and the associated beam-breakup integral $B.(6)$ For fusion laser systems the figure-of-merit for a Faraday rotator material is

nV/n_2 where n = linear refractive index, n_2 = nonlinear refractive index, and V = Verdet constant at the laser wavelength.

Based upon this figure of merit, the presently "best" Faraday rotator material is FR-5 which was selected for use in the Shiva laser. These rotators are located in twenty Beta disk stages (10 cm aperture), the twenty δ disk stages (20 cm aperture), and in four B rod stages (5 cm aperture). The large 20 cm rotator has a thickness of only 1 cm to minimize the B value of the output stage.

Optical Specifications

Detailed optical specifications have been developed for all of the Shiva optical components. These specifications represent a compromise between the desires of the laser physicists for perfect optics and realistically achievable and affordable optical quality. Table 4 tabulates the specified single pass wavefront tolerance at $0.6328 \mu\text{m}$ for all the active glass (laser disks, laser rods, Pockels cells and Faraday rotators) used in the system. Similarly, Table 5 summarizes the homogeneity specifications for the active glass components and provides the statistics concerning the percentage of components requiring hand figuring to achieve the specified homogeneity.

Table 4
Specified Wavefront Tolerance for Single Pass Transmission at $0.6328 \mu\text{m}$.

Part	Peak to Valley	Gradient
α Rod	$\lambda/6$	$\lambda/12$ per cm
β Rod	$\lambda/6$	$\lambda/12$ per cm
β Disks	$\lambda/12$	$\lambda/30$ per cm
γ Disks	$\lambda/10$	$\lambda/30$ per cm
δ Disks	$\lambda/8$	$\lambda/40$ per cm
β Rotator	$\lambda/10$	$\lambda/25$ per cm
δ Rotator	$\lambda/8$	$\lambda/40$ per cm
α Pockels cell	$\lambda/8$	$\lambda/10$ per cm
β Pockels cell	$\lambda/8$	$\lambda/10$ per cm

Table 5
Homogeneity Statistics as of August 1, 1977

Part	Specified Homogeneity	Quantity Ordered	Percentage Requiring Hand Figuring	Approximate Magnitude of Glass Homogeneity Before Hand Figuring
α Rods	$\pm 1.3 \times 10^{-7}$	28	96%	$\sim \pm 5 \times 10^{-7}$, fairly symmetrical, not a severe problem
β Rods	$\pm 1.3 \times 10^{-7}$	33	100%	$\sim \pm 10 \times 10^{-7}$ average, frequently to $\pm 20 \times 10^{-7}$, quite unsymmetrical.
β Disks	$\pm .9 \times 10^{-6}$	450	5%	Mostly undetectable.
γ Disks	$\pm .9 \times 10^{-6}$	100	97%	$\sim \pm 4 \times 10^{-6}$, but unsymmetrical, gradient difficult to control in figuring.
δ Disks	$\pm 1.0 \times 10^{-6}$	75	0	About 1/4 of disks have been finished. So far no figuring required and test data from factory indicates none will be.
β Rotators	$\pm 2.2 \times 10^{-6}$	25	0	Mostly undetectable, no figuring required.
δ Rotators	$\pm 3.9 \times 10^{-6}$	25	32%	$\sim \pm 5 \times 10^{-6}$ very slight symmetrical figuring (parts are thin, hence relatively large Δn).

Our procedure is to measure the optical parameters of the individual elements to insure conformity to specification and also to subject all final assemblies to a final interferometric evaluation. This verifies both the elements and the assembly technique.

We have assembled 62 Beta disk amplifiers each containing six laser disks. All these amplifiers have been placed in a Fizeau interferometer and inspected for the accumulated disk distortion. The interpretations

of the amplifier's optical quality were divided into the following three categories:

- 1) Amplifiers with single pass 1.06 micron distortion of between $\lambda/20$ and $\lambda/15$.
- 2) Amplifiers with distortions of between $\lambda/15$ and $\lambda/10$.
- 3) Amplifiers with distortions of between $\lambda/10$ and $\lambda/5$.

Thirty of the amplifiers were in the first category, twenty-nine were in the second category, and only four were in the third category. These measurements were made at 80% of the aperture and a number of the amplifiers showed about $\lambda/4$ flatness on the outer edge. Eight of the amplifiers have fringe patterns which exhibit a slight amount of astigmatism.

Laser Damage to Optical Components

The high power laser pulse being propagated down a Shiva laser chain can do significant damage to optical components in the system. The areas of potential damage are: in the bulk glass through which the beam passes; at the polished surface of the bulk glass; or in the dielectric thin-film coating required for some optics. By proper choice of finishing compound, elimination of platinum inclusions in the glass and proper cleanliness, damage to bare polished surfaces and bulk glass is not a limiting factor. However, laser damage in dielectric thin film coatings is a serious problem for the Shiva laser and is the performance limiting factor for laser pulses in the range of 0.5 to 1.0 nanosecond.

Fortunately the 500 laser disks used in Shiva are at Brewster's angle and therefore do not need thin film coatings for enhanced transmission of the P polarized laser beam. However, there are three other types of surfaces which require coatings. These are:

- 1) Polarizers, which are at Brewster's angle, but require a multilayer coating (about 30 layers) on one surface for the purpose of filtering any S polarization component, while minimizing attenuation of the P state.
- 2) Lenses, Faraday rotators, and windows used at approximately normal incidence, which need to be coated to enhance transmission, reduce multiple reflection images, and reduce multiple reflection induced phase modulations in the beam.
- 3) Mirrors and beamsplitters, which in the case of the large turning mirrors are close to 100% reflectors, but with a carefully controlled small amount of transmission (on the order of 2%) for diagnostics purposes.

All these coatings are subject to laser-induced damage; however, because high reflectivity coatings have higher damage levels⁽⁷⁾, and because of the way laser chains are staged⁽⁸⁾, the anti-reflection coatings on input spatial filter lens are the weak link in large laser systems. Reference (7) summarizes the damage tests results for the coatings we are using and for future coatings.

We are actively working with vendors to increase the damage threshold of thin film dielectric coatings, and the achievement of increased damage threshold levels appears attainable. Recent analysis and experiments indicate that the damage level achievable may be limited by the strength of the electric field in the high index material. In some instances, in particular high reflectance mirrors, designs can be modified to reduce these fields while at the same time maintaining desired optical performance. For anti-reflection coatings, however, the best hope lies in the ability to close the gap between average damage results on "production" items and the ultimate limits as inferred from theory and seen on small areas of small samples. It appears that what is achieved on the average at the present time and what might be achievable through technique improvement is at least a factor of two.

Future

We are currently doing preliminary design of a larger laser system called Shiva Nova that would be capable of an order of magnitude greater performance. This system would require much larger optical elements in larger quantities than Shiva. Supplying these components would severely tax the optical industry over a period of several years.

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