

Quantitative Stress-Induced Birefringence Measurements of Large Optics by a Prototype Imaging Polarimeter

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1. Introduction

The National Ignition Facility is a next generation inertial confinement laser with approximately 7,000 large optics (0.5 m x 0.5 m) in 192 separate lasers with each beam needing minimal wavefront aberrations to maintain the desired spot size upon the target. Since the laser cavity design uses polarization switches and phase-matched frequency conversion crystals, it is sensitive to polarization aberrations distributed among the 250 large optics in each beam. As the majority of the elements are transmissive elements, (such as amplifier glass slabs, vacuum windows, spatial filters and focal lenses); it is imperative to qualify that each transmissive element does not modify the polarization state of the incident linearly polarized beam. The primary aberration error of a transmissive optical element due to optomechanical mounting is stress induced birefringence, which interacts with the linear polarization state of the laser to create a spatially varying optical path difference (OPD) across the beam. The spatial variance in OPD caused by the stress induced birefringence is seen by a traditional interferometer as wavefront aberration (assuming linearly polarized light), and the small amount of birefringent retardance can also be directly measured using a large aperture imaging polarimeter. It has been proposed to replace the interferometric testing of all transmission elements with polarimetric measurements to both reduce environmental sensitivity and to quantitatively measure the stress-induced birefringent retardance. This paper discusses preliminary results from a prototype imaging polarimeter that can measure the spatially varying retardance of an element placed in a beam of linearly polarized light to less than 1 nm RMS.

2. System Concept

Imaging polarimeters have been developed by various groups for single point and area measurements of polarization states and birefringence in the last few years.^{1,2,3} The imaging polarimeter developed to measure NIF optics incorporated a rotating retarder and simulated the linearly polarized input polarization state expected for the laser while detecting spatially varying retardance due to stress induced birefringence. Because the expectation is that the birefringence approaches zero, a Taylor series approximation was made to reduce the involved Mueller matrix intensity solution of the system to a simple sinusoidal phase dependence where retardance was measured using tradition synchronous detection techniques. Taking two measurements with the

initial linear polarization state rotated 45 degrees for the second, the system sensitivity to the fast axis angle of the sample can be determined and eliminated.

The optical layout of the system is shown in Figure 1. Combining quartz halogen and fluorescent tubes inside a light box created a spatially incoherent extended light source. The light passes through a vertical oriented polarizing sheet of Polaroid HN38S before reaching the sample. Following the sample are two converging lens used in a Newtonian telescope configuration to reduce the size of the light beam for one-inch aperture optics. Light baffles are employed between the imaging optics and the large collimation lens to reduce scattered light into the detector. A computer controlled rotation stage rotates a quarter-wave plate placed directly after the small converging lens in the collimated optical path. A final linear analyzer is crossed with respect to the initial polarizer followed by a 10-nm bandwidth interference filter centered at 632.8 nm with a simple lens imaging the sample under test onto a Cohu CCD camera array.

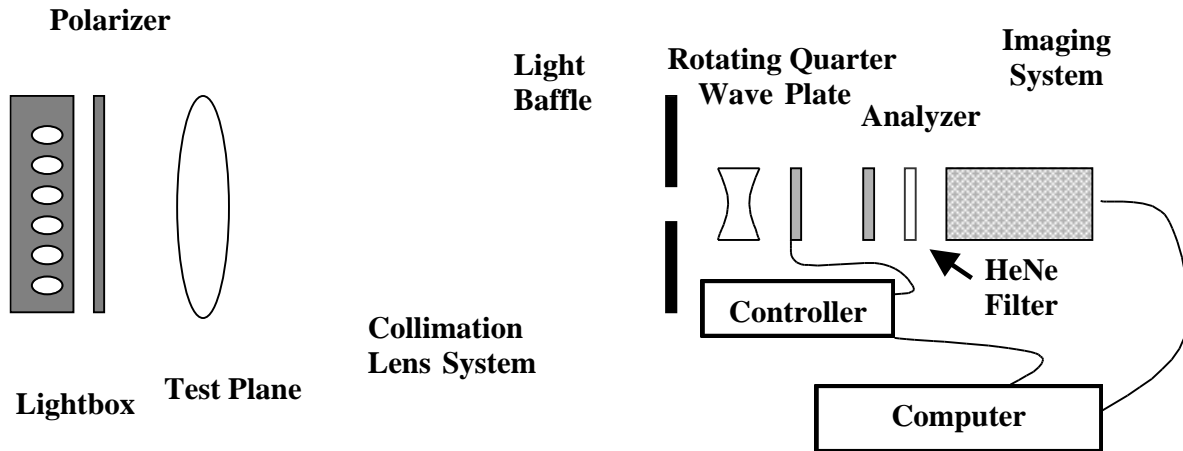


Figure 1: Schematic layout of prototype imaging polarimeter for measuring large optics

The spatial intensity of this polarimeter oscillated as a sinusoidal function repeating with every 90° of revolution of the quarter wave plate. (Equation 4) This angular functional dependence allowed synchronous detection techniques^{4,5} to calculate sample retardance very accurately. For this instrument, a simple 4, 12 or 24 step algorithm evenly spaced over one complete period, 90 degrees, of the output intensity is employed. Multiple image frames or integration buckets (15, 30 or 60) are taken to reduce the noise in the measured retardance.

With only a single input polarization state, there is a cosine law sensitivity to fast axis angle for this type of imaging polarimeter. For an input polarization state perpendicular or parallel to the sample fast axis, the sensitivity of the instrument to retardance drops to zero. Likewise, when the sample fast axis angle is ± 45 degrees with respect to the input polarization state, the instrument has a maximum sensitivity. To effectively map sample retardance at all fast axis angles, two measurements are made; one at an initial polarization angle and the second with an input polarization state rotated 45° with respect to the first measurement. The two measurements are then root sum squared for a fast axis insensitive magnitude.

3. Theory

The imaging polarimeter can be represented as a transfer function of the light exiting the lightbox to the light detected by the CCD camera. A Mueller matrix⁶ is assigned to each polarization element of the optical system. Upon multiplication, a system transfer function is

obtained as a function of the angle of the quarter wave plate and the angle of the fast axis angle of the sample. From this analysis, the normalized instrument output light intensity is represented as

$$I = 1 - C^2 * (c^2 + s^2 * \mu) - C * S * c * s * (1 - \mu) + S * s * \mu \quad (1)$$

where $C = \cos(2\theta)$ and $S = \sin(2\theta)$ for the quarter-wave plate, $c = \cos(2\phi)$ and $s = \sin(2\phi)$ for the sample, $\mu = \cos(\delta)$ and $\mu = \sin(\delta)$ for retardance of the sample, θ is the angle of the quarter wave plate with respect to the polarizer, ϕ is the fast axis angle of the sample, δ is the sample retardance, and unit input intensity was assumed. For small retardance, using a Taylor series expansion, setting $\sin(2\theta) = 1$, and grouping like terms, Equation 1 reduces to

$$I = \left(\frac{1}{2}\right) \cos(4\theta + \delta) \quad (2)$$

which is the basic form for using synchronous detection phase-shifting techniques to find δ .

4. Experimental Results

Retardance images from the prototype imaging polarimeter are shown in Figures 2 and 3. Referring to Figure 2, plastic safety glasses were placed in the object plane of the instrument and the phase retardance due to internal stress in the plastic is illustrated. Figure 3 shows a NIF sized vacuum window optic approximately one-inch thick demonstrating stress induced birefringence due to a compressive point stress field. This image reflects a single measurement using linearly polarized light and demonstrates the variable sensitivity of the instrument due to fast axis angle of the test sample. The magnitude of the retardance due to stress induced birefringence matches that found using interferometric techniques to measure this same effect.⁷ The noise floor of the full aperture empty cavity is measured as 0.33 nm RMS retardance. Circular streaks in this image indicate the noise floor may be limited to the tolerance of the quarter wave plate, quoted as $\lambda/350$ by the vendor. Difference measurements were taken between two successive retardance maps using differing numbers of phase steps and integration buckets to estimate its effect on repeatability of the imaging polarimeter. A standard of 12 steps, 60 integrating buckets was chosen with the RMS retardance across the full aperture was measured as 1.0 nm. The retardance phase maps were analyzed within Wyko image processing software.

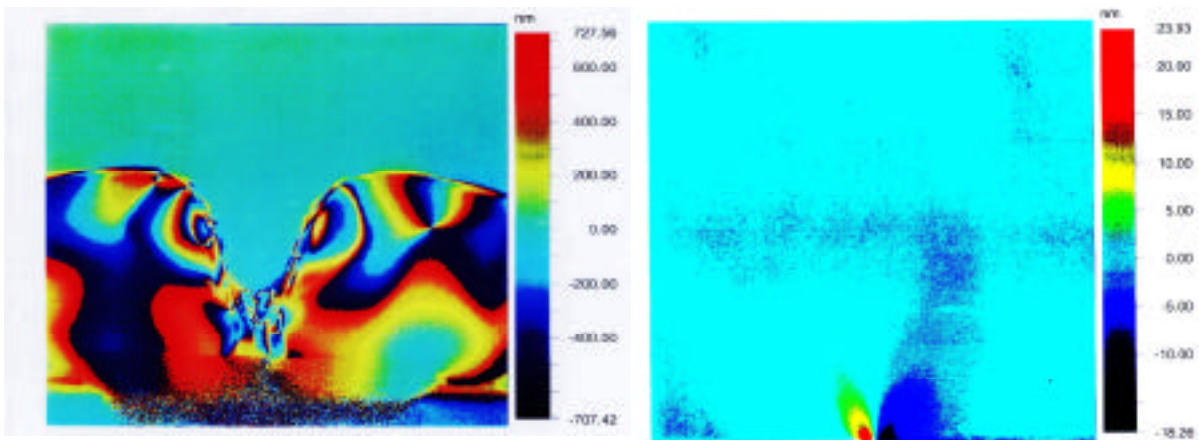


Figure 2: Retardance map of plastic safety glasses measured by imaging polarimeter

Figure 3: Retardance map of test window resulting from a point stress field

Error sources for this imaging polarimeter draw from both classical polarimeters and phase shifting interferometry algorithms. Systematic polarization dependent errors include those associated with a finite extinction of orthogonal polarization states for the polarizer and analyzer, spatially varying retardance of the quarter wave plate and mean retardance of the quarter wave plate varying from 90 degrees. Other sources of error are sample retardance so large that the small angle approximation resulted in analysis errors of the retardance phase maps and use of a finite bandwidth instead of monochromatic light for illumination. Possible element alignment errors happen when the transmitted light may not have been normal to the quarter wave plate. At very low stress backgrounds in the current system, there is some residually birefringent retardance of each system optical element that interacts with the sample polarization state. Errors associated with phase shifting interferometry algorithms include quantization effects due to sampling the retardance phase map with a digital CCD camera array, phase shifting errors from inexact rotation of the rotary stage and electronic and photon shot noise. Other error sources include time varying intensity fluctuations of the extended polarization source, residual scatter from individual optics, and thermal effects that contributed asynchronous errors into the system.

V. Conclusions

A prototype imaging polarimeter is developed that measured retardance due to stress induced birefringence of large optics. A synchronous detection scheme is utilized in the measurement of retardance. The instrument has a variable sensitivity due to fast axis angle of the sample being tested which is remedied by making two measurements with a linear input polarization state that rotated 45 degrees. This polarimetric technique is inherently less sensitive to environmental noise than interferometric techniques to measure stress induced birefringence and is able to measure residual retardance of assembled large optics within the tolerance required by the National Ignition Facility project

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