Low-birefringence lens design for polarization sensitive optical systems

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ABSTRACT

Polarization sensitive optical systems may contain optical components that are considered non-polarization optics, such as multi-element collection/illumination lenses, relay lenses and focusing/imaging lenses. With conventional optical design and optomechanical software tools to design these lenses, special consideration is required in choosing glass materials, coatings, and optomechanical design for low intrinsic and stress-induced birefringence and thermal stability. Optical design parameters are discussed to achieve overall minimum birefringence, by optimizing with low intrinsic birefringence glass material, applying phase-controlled (balanced) coating design, and low stress mechanical design approaches. Also discussed are options for matching thermal expansion coefficient (CTE) of the system components. Analysis on transmissive phase retardation of a microbjective at its pupil plane, as well as its birefringence measurement data, will be presented. It is shown that it is critical to design and optimize at multiple positions across the lens pupil to achieve better polarization performance.

Keywords: polarization, lens design, birefringence, coating, athermal, stress, phase, retardation.

1. INTRODUCTION

The international standard on optics and optical instruments (ISO 11010-2) lists a guideline for typical birefringence tolerance in several applications for optical systems made of isotropic material. For polarization and/or interference instruments and precision optics, the permissible optical path difference through the system is less than 2nm/cm and 5nm/cm, respectively [1]. Polarization sensitive instruments incorporating precision optics are commonly used in micron-level inspection for both magnitude and phase information. They are also utilized in petrology, mineralogy, geology, crystallography, and biology for identifying small features in materials. When an optical system is used in a polarization sensitive environment, each component of the system is limited to a certain contribution. The contribution could be divided into three categories: (1) optical birefringence, (2) optomechanical birefringence, and (3) birefringence from environmental change. We review the design considerations and characterization of a precision lens that requires a maximum birefringence of 2nm/cm.

Birefringence is defined as the double refraction of light in a transparent, molecularly ordered material. It is due to orientation-dependent differences in refractive index. Optical birefringence includes lens material intrinsic birefringence and inherent phase shifts in the thin film coatings. This paper mainly discusses phase shifts in the thin film coating since many transparent solids are optically isotropic, with index of refraction equal in all directions throughout the crystalline lattice. Glasses are typically treated as isotropic material with the exception of crystalline materials, such as $CaF2$. Optomechanical birefringence is a stress-induced birefringence, the magnitude of which is determined by stress-optical coefficients of the glass and the mechanical stress exerted on it. Lenses are typically held using mechanical mounting methods and the interface between the optical element and the mechanical element will produce stress and result in a change in the optical path. In this paper, we review the stress-optical coefficients (photoelastic constants) for some common lens materials, which represent residual stress during the glass material fabrication process. Mounted lenses inside the optical instrument operate in a thermal environment. Any change in this environment may alter the material

properties and the mechanical stress. A low birefringence lens design needs to minimize optical and optomechanical birefringence in a thermal environment.

In this paper, we report several phase-controlled anti-reflective (AR) coating designs for a broad waveband, diffraction-limited microbjective at F/1.6. Phase information across the objective pupil is plotted. To evaluate the pupil effect, a simple birefringence test is proposed and described with measurement results.

2. BIREFRINGENCE IN LENS MATERIAL

2.1 Stress-Induced Birefringence

Birefringence can be caused by inherent stress in lens material, which is a mechanical effect during the annealing process [2]. The difference in the optical path inside a material sample can be represented as

$$OPD = K \cdot d \cdot \sigma \qquad (1)$$

Where K is the stress optical coefficient (mm^2/N) or photoelastic constant (10^{-12} Pa, or Brewster) of the material, d is light path in the sample, and σ is the mechanical stress. The coefficient K is temperature and wavelength dependent. Figure 1 shows the stress-optical coefficient values for common lens materials, measured at 21°C at a wavelength of 589.3nm.
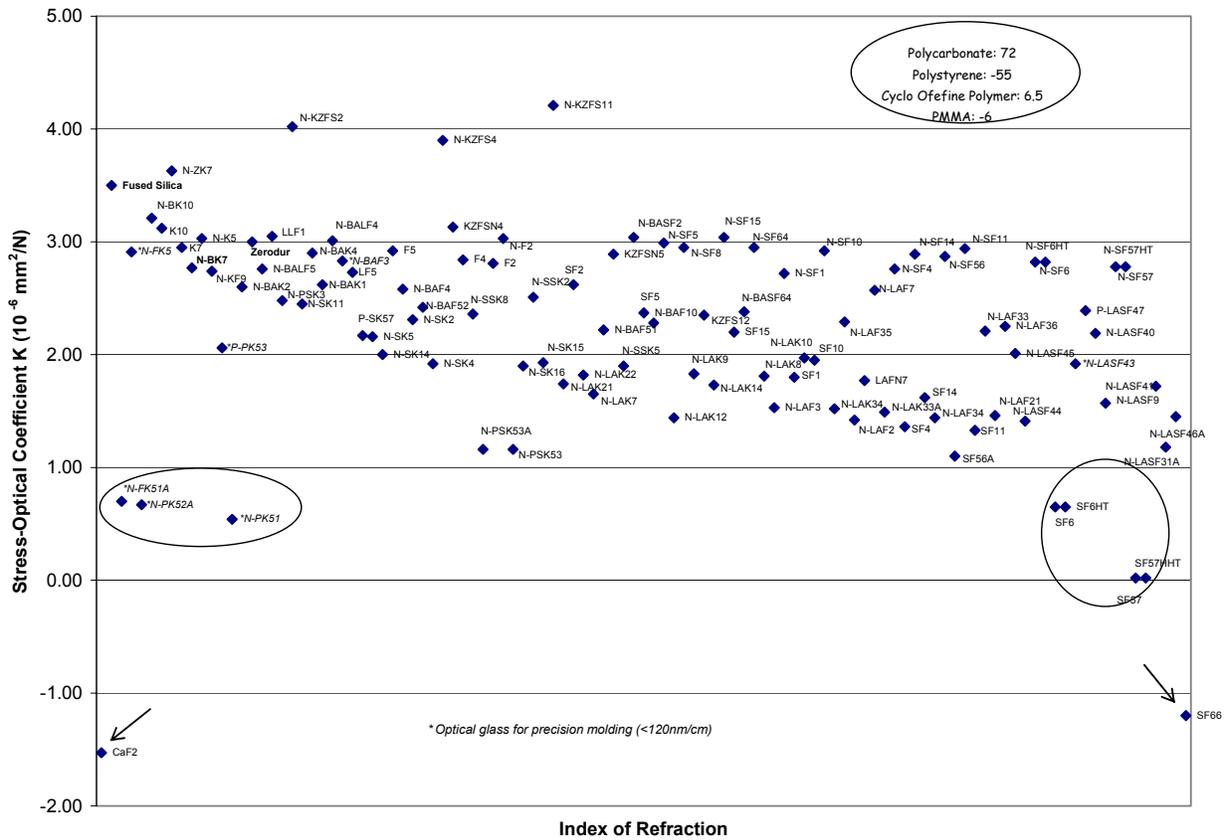

Figure 1: Stress optical coefficient of commonly used lens materials.

For most of the glasses, the stress-optical coefficient is between 0 and 3. Low index glasses, N-FK51A, N-PK52A and N-PK51 and high index glasses, SF6 and SF57, have good stress properties. CaF2 is an anisotropic crystalline material utilized heavily in ultra violet applications whose K value listed here is its biaxial property, known as q_{11}-q_{22} [3].

Stress-Induced birefringence can be reduced in glasses by a material annealing process. If a lens design demands critical low stress birefringence, selection of glasses with low stress-optical coefficient and higher grade of stress birefringence qualification is necessary.

2.2 Intrinsic birefringence

Intrinsic birefringence exists in cubic crystalline material, commonly used in short wavelength applications. It is a deviation of refractive index which cannot be reduced by the growth process [3, 4]. An ideal crystalline material with cubic-symmetry behaves like an isotropic and nonbirefringent glass material with substantial directional and polarization dependence. This makes the optical design more complex and introduces additional design parameters requiring correction.

In the deep UV, a cubic crystal's microscopic intrinsic birefringence becomes problematic. Typically, precision UV grade CaF2 lenses are made with the optical axis of the lens along the [111] crystal direction. For paraxial rays traveling along the [111] direction, there is zero or low birefringence and index variation. For a circular lens with a given numerical aperture, only the variation in the index for propagation within the included angles will matter. Because birefringence is zero for propagation along the [111] direction and small close to that direction, the full effect of the birefringence can be neglected for small NA. In high NA systems, however, the birefringence effect is much more severe due to the rapidly changing radial birefringence for large ray angles deviating from the optical axis. The maximum effect is realized for propagation angles of 35.26° (or 45° for the [100] directions) within the material [3].

3. PHASE RETARDATION IN COATINGS

When light is incident on an interface between media of different refractive index, part of the light is reflected and part of it is transmitted. If an optical system consists of several elements with high index of refraction or if the system has a large number of surfaces, then the light that is reflected can be a significant problem both on the grounds that it is lost from the main beam, so that the image is reduced in intensity and also because some of the light that is reflected turns up at the final image plane in the wrong position. Contrast of the image is thereby impaired. The reflection coefficient at normal incidence at a surface of refractive index n in air is given by R= [(n-1)/ (n+1)]^2. Typical optical refractive indices are between 1.45 – 4.0 and hence R=3.4 – 36% for one surface. Applying an Anti-Reflection (AR) layer on a component, such as a condenser lens, can achieve very low reflectivity down to R<0.05%.

An important phenomenon of AR coating, which also impacts an optical system, is its transmissive phase retardation. Although much effort is concentrated on reducing reflection loss, often the phase retardation of a coating is not considered. Some systems, especially those with high numerical apertures, have rays incident at large angles towards edge of the clear aperture, and are more sensitive to coating phase retardation. The system transmission is a product of transmission of each element including glass internal transmission and coating transmission. Transmissive phase retardation Δ_{s-p}, on the other hand, is a sum of individual phase retardation at a surface and at a specific pupil position, provided the lens elements are isotropic. Therefore,

$$T = \prod_{i=1}^{n} t_i, \quad \Delta_{s-p} = \sum_{i=1}^{n} \delta_i \qquad (2)$$

Where n is the number of surfaces with AR coatings. Although the element transmission t_i is always positive, the phase retardations, δ_i, at different coating surfaces may have different signs, and multiple coatings could have a corrective controlling effect on phase retardation under appropriate circumstances. This has important implications in design practice because it is possible to minimize or reduce the total transmissive phase retardation Δ_{s-p} even if each element retardation δ_i is finite.

As we know, most of the optical elements in optical instruments require thin film coatings to reduce reflection loss. Coatings improve light throughput, but at the same time, they introduce polarization due to their thin film interference effects. Most of the time, these two functions of thin-film coating are working against each other. To optimize coating reflection/transmission performance with minimum phase shift requires trade-offs and most importantly a balanced coating design.

To apply a phase-controlled coating design with minimized reflectance, designers will consider substrates, as discussed in Section 2, and a plurality of superimposed thin film transparent layers deposited on these substrates. The dielectric layers of the superimposed film are made of optical coating materials of substantially different indices of refraction, and often alternating high- and low-index quarter-wave layers. The optical thicknesses of the layers are optimized so that they satisfy the transmission and the phase retardation requirements in order to produce both maximum transmission and a specific phase shift, within the specified wavelength range and at a specified angle of incidence.

Thin film coatings deposited at elevated temperatures may exhibit substantial residual stresses induced by growth strains and/or thermoelastic strains that develop during the cool-down period. A comprehensive description of these stresses includes not only the normal stresses in the film layers and the substrate but also the interfacial shearing stresses, which sometimes may cause delamination to occur.

4. STRESS-INDUCED BIREFRINGENCE IN LENS ASSEMBLIES

Isotropic material may become anisotropic under mechanical and thermally induced stress, and the refractive index inside the material becomes locally anisotropic. The permanent stresses resulting from the annealing process, as mentioned in Section 2, and the inhomogeneities of refractive index are generally very small. However, if extraordinarily good optical homogeneity is required for precision optics, the change in refractive index caused by the small residual stress can be meaningful. The high stresses in thermally strengthened glass sheets, such as those used as windows in high-pressure chambers, causes noticeable changes in refractive index. In general, temporary stresses caused by temperature variations have a more significant effect in large optical systems than in small ones. It is important to ensure that optical components are assembled in a nearly stress-free mounting mechanical housing and thermal expansion coefficients of the optical and mechanical elements must be matched as closely as possible.

4.1 Mechanical Stress

Mechanical stress modifies the refractive indices of optical elements in directions parallel and perpendicular to the stress direction, resulting in wavefront and polarization errors in the optical system. The system will become anisotropic and inhomogeneous due to the stress birefringence. Stress birefringence at each point of an isotropic material can be calculated by the state of stress and stress-optic coefficients of the lens elements [5].

$$\Delta n_{1\text{-}2} = \Delta n_1 - \Delta n_2 = K \cdot (\sigma_1 - \sigma_2) \tag{3}$$

To minimize mechanical stress, lens designers need to consider glass properties and lens mounting methods. Reference 6 discusses mounting stresses in optical components, and ways to estimate stress for different types of mounting schemes.

4.2 Thermal Stress

Changes in temperature will cause differential expansion or contraction of optical elements with respect to mounting materials in both axial and radial directions. The refractive indices may thus be anisotropic due to the thermal stress induced by such expansion or contraction. The effects of a temperature change on a multi-element lens with various mounting schemes were discussed in Reference 7. The coefficient of thermal expansion (CTE) of the mount is usually higher than that of the optical component. CTE mismatches between the optical glasses and the mounting materials induce stress in the optical glass, especially when there are cements and mounting adhesives involved. The thermal stress eventually becomes mechanical stress, and this may make the optical system show increased stress birefringence. When the light source in an optical system is a laser, its beam distribution across the optical clear aperture will add

another inhomogeneous complexity to the thermal distribution on the optics and mount. To minimize thermal stress, designers often use Invar as mounting material, and choose close CTEs of the optical elements inside the mount. Different low thermal stress mounting methods are developed for this purpose [8, 9].

Assembly failures can happen when there is excessive thermal stress. However, CTE matching in the system may not be practical, and often CTEs of elements are constrained by other design parameters. So minimizing the CTE differences of the design materials is important in achieving thermally stable performance. An athermal element mounting scheme therefore will reduce the risk of thermal stress in the system.

5. EXAMPLE – A MICROBJECTIVE IMAGING LENS

In this paper, we look into optical birefringence in coating design, and describe several coating design approaches for a diffraction-limited microbjective, designed for an F/1.6 aperture and a broad waveband centered at 633nm. This is a multi-element lens which has doublets to correct chromatic aberration and high index glass materials to correct spherical aberrations across the pupil. In addition to typical requirements for an imaging microbjective, it also specifies as-build stress birefringence to be less than 2nm/cm over an ambient temperature +/-2.5°C. This requires that the optical design should minimize all of the contributing factors to birefringence while leaving enough tolerance for process related errors. So the design needs to consider permanent stress birefringence in the material and coating phase variation across the clear aperture (while the reflectance of each AR coating design needs to meet overall transmission requirement). At the same time, glasses must be chosen with close coefficients of thermal expansion (CTE) and low stress mechanical mounting methods employed.

Based on the discussion in Section 2, we are able to choose glasses with K values up to 1.8×10^{-6} mm^2/N. Glass CTEs range from 6 to 8×10^{-6}/K. A special athermal mechanical mount is designed with stainless steel (CTE ~11×10^{-6}/K) to reduce potential mechanical stress. The objective has six (6) surfaces that require AR coating to reduce reflection loss.
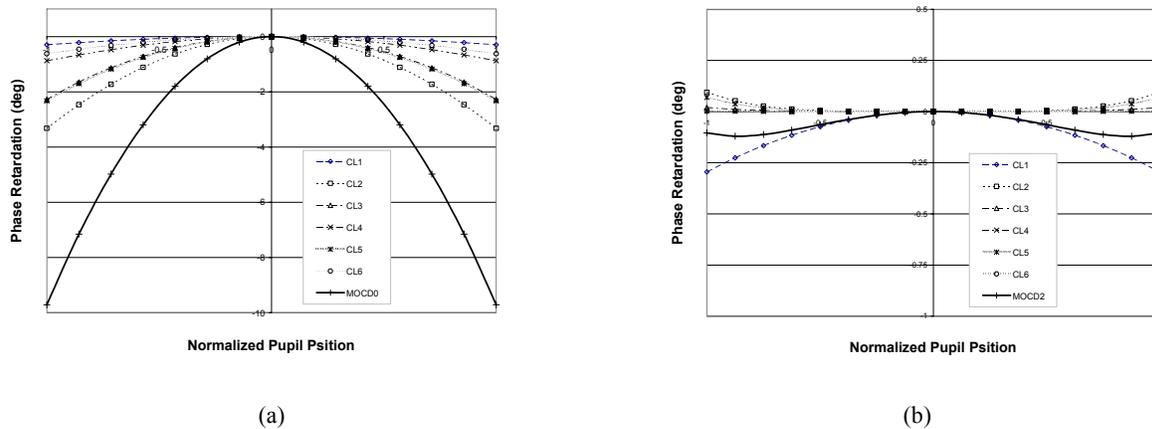

(a)   (b)

Figure 2. Phase retardation across the pupil for each coating layer δ_{s-p}. Also plotted is transmissive phase retardations Δ_{s-p} for (a) MO-CD0 and (b) MO-CD2 at pupil of the microbjective.

Figure 2 shows phase retardations δ_{s-p} for each six (6) AR coated surface, from CL1 to CL6. The transmissive phase retardation Δ_{s-p} is also plotted accordingly over the pupil. In Figure 2a, MO-CD0 represents a set of multi-layer coating design which is concentrated on achieving smallest reflectance performance. The phase change at edge of the pupil, however, shows the coatings will introduce excessive amount of birefringence towards edge of the clear aperture. To reduce the edge phase effect, we have studied six different AR coating designs, all of which meet the objective transmission requirement but with different transmissive phase retardation results. As shown in Figure 3, they are labeled as MO-CD0 to MO-CD5. Multi-layer AR coatings are designed on some of the surfaces which are less sensitive to phase change. At these surfaces, marginal ray angles of incidence are relative small. At other surfaces with large

angles of incidence, the AR coatings are carefully designed to compensate each other for the phase change. Some of the surfaces are coated with single layer coatings.

With emphasizes on the phase control, coating designs MO-CD2, MO-CD3, MO-CD4 and MO-CD5 have improved the transmission phase retardation. They show significant improvement at edge of the pupil. For the low birefringence requirement, coating designs such as MO-CD2 have to enable each surface's coating as a phase optimizer. Thus all AR coatings for different substrate surface will be designed or optimized together in the optical system for a balanced transmission and phase shift performance. In the MO-CD2 coatings, each of six (6) AR coated surfaces has less phase variations. It yields a smaller Δ_{s-p} at the pupil by taking advantage of the phase terms with different signs at specific pupil positions.
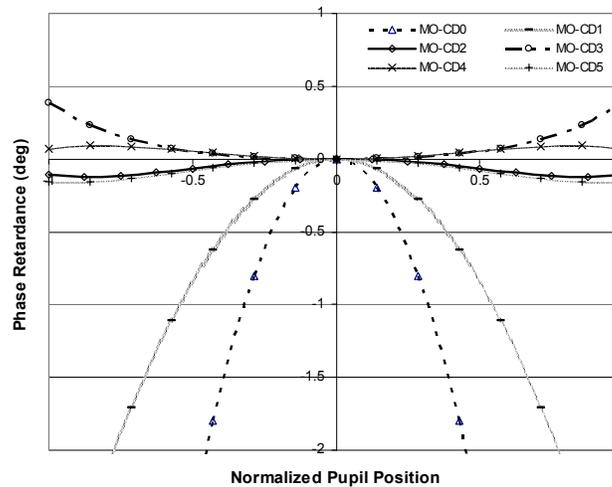

Figure 3. Phase retardation for six (6) different AR coating design approaches. MO-CD0 has multi-layer AR coating on every single surface of the lens elements which yields the best transmission performance for the objective; MO-CD2, MO-CD3, MO-CD4 and MO-CD5 have phase-controlled or balanced AR coating designs across the pupil.

A note to the analysis in this paper is that all the phase retardation values are obtained at the objective pupil plane under the assumption that all coatings are uniform and symmetrical across the pupil. Coating design MO-CD2 is employed to objective prototypes and evaluation of their birefringence is discussed in following section.

6. BIREFRINGENCE TEST AND MEASUREMENT DATA

Typically, retardation is measured using polarized light microscopes equipped with manually adjustable compensators which are single-point measuring devices. The process consists of adjusting a compensator until the point of interest in the field of view is compensated to zero and reading the compensator dial, thus providing a measure of the birefringence retardation at that point. The process may take several minutes for each measurement and requires a thorough understanding of polarized light optics. It can be particularly time-consuming if a large number of measurements need to be made over an area of interest rather than at a single point.

Birefringent materials feature two orthogonal optical axes with distinctly different refractive indices. Light polarized parallel to one axis travels at a different speed through the sample than light polarized parallel to the orthogonal axis. As a result, these two light components, which were in phase when they entered the sample, exit the sample out of phase. This phase retardation may be used to determine its birefringence.

We can calculate birefringence from measured retardation if we assume uniform, or approximately uniform, stress along the light path. This is usually the case if the thickness along the light path is small relative to the dimensions orthogonal to the light path, or if the sample is unconstrained in one of the directions orthogonal to the light path. If these conditions are met, the conversion from retardation to stress is straightforward.

Designers often use different models to determine and minimize stress. If the model is accurate and predictive and able to handle complex optomechanical process, then the results should be verified by and close to measurement data. Complex polarization models and instruments are beyond the scope of this paper. However, a simple measurement method and setup is proposed. A polarimeter for the birefringence test was developed in Melles Griot. An optical bench diagram for measuring lens retardation is shown in Figure 4. A laser is used as a light source, followed by a polarizer orientated at +45° with respect to x-axis. Transmistted light passes through the lens under test with a retardation δ_L and a reference lens (as known δ_R or an identical lens δ_L could be placed to obtain average test result). The light then passes through an analyzer at -45°, and goes into a photodetector.
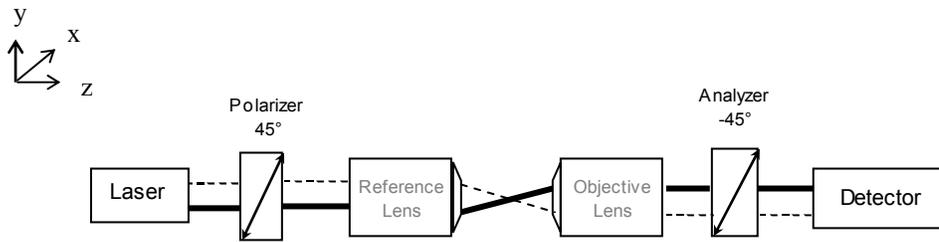

Figure 4. Experiment setup for birefringence measurement

We assume that the lens is a linear retarder between two ideal plane polarizers and ignore scattering loss in the lens under test. Using the Jones matrix, the electric field vector reaching the detector is given by

$$\vec{E} = \sqrt{\frac{I_0}{2}} \begin{bmatrix} \cos^2\theta & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \sin^2\theta \end{bmatrix} \begin{bmatrix} \cos(\frac{\delta}{2}) + i\cos(2\rho)\sin(\frac{\delta}{2}) & i\sin(2\rho)\sin(\frac{\delta}{2}) \\ i\sin(2\rho)\sin(\frac{\delta}{2}) & \cos(\frac{\delta}{2}) - i\cos(2\rho)\sin(\frac{\delta}{2}) \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{4}$$

Where,
- I_0 is the light transmission when the polarizers are parallel and no lens is present.
- θ is the angle between the axis of second polarizer and the x-axis
- δ is the retardation of both lenses
- ρ is the fast axis direction

The intensity equation simplifies for the case of crossed polarizers

$$I = I_{in}T\cos^2(2\rho)\sin^2(\delta/2) \tag{5}$$

Where I_{in} is the input light intensity; T is the transmission of the optical system. If we rotate the sample we should be able to find the maximum output which corresponds to $\rho = 0°$ or $\rho = 90°$. Then,

$$I = I_{in}T\sin^2(\delta/2) \tag{6}$$

For light with a test wavelength λ, the average birefringence of a retarder of retardance δ_L and thickness d can be written as,

$$\Delta n = \frac{\delta_L \lambda}{2\pi d} = \frac{\lambda}{2\pi d} \arcsin(\sqrt{\frac{I}{I_{in}T}}) \tag{7}$$

For a measurement accuracy of $\delta = 0.2°$, a pair of crystal polarizers are chosen, each with an extinction ratio of 10^{-6}. With a 5mW 633nm laser and two such polarizers, the light power entering detector is at maximum 14.25nW. This indicates the measurement needs to be in a low noise test environment. This can be achieved by operating in a dark room or by modulating the test beam.

Figure 5 shows an average measured birefringence for the objective. The dashed line, for comparison, is the theoretical contribution from the coating alone. The difference between these two curves represents stress-induced birefringence and measurement error. It shows that birefringence at the edge of the pupil is significantly larger than on axis. Maximum stress birefringence from this measurement is less than 0.7 nm/cm.
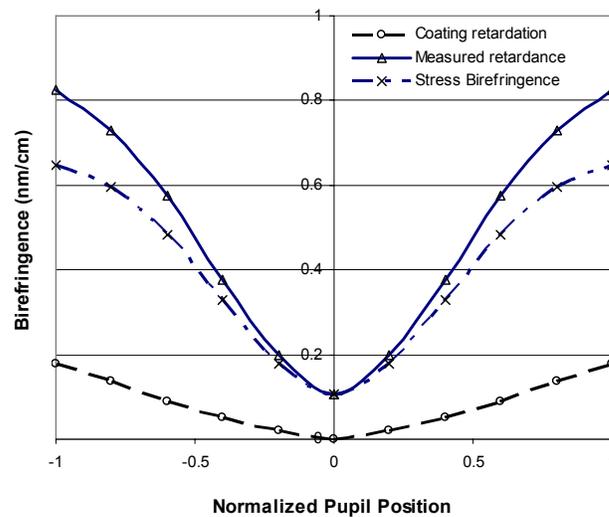

Figure 5. Average measured birefringence in the objective, using a Melles Griot proprietary mechanical design and coating design MO-CD2. Also plotted is the converted coating phase shift for comparison.

7. SUMMARY AND CONCLUSIONS

We have discussed three categories of birefringence which designers need to consider for polarization sensitive optical systems. Stress-optical coefficients of some common lens materials are reviewed. We have discussed phase shift in AR coating design and total transmissive phase retardation as a function of pupil position. A phase-controlled coating is emphasized for a precision optics in design stage to achieve low birefringence performance. This technique, along with an athermal low stress mechanical design may be critical for a successful optical design with less than 2nm/cm birefringence requirement. A birefringence test method is proposed using crystal polarizers with high extinction ratio. An experiment on a diffraction-limited microbjective was performed to evaluate its stress birefringence across the lens pupil. With coating phase shift prediction, we are able to estimate stress induced birefringence at certain pupil positions. This can also be used to verify stress birefringence modeling for polarization sensitive optical systems.

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