Variation in optical disc retardance measurements

Kent B. Rochford, Steve T. Kreger, and John West
Optoelectronics Division
National Institute of Standards and Technology
325 Broadway, Boulder, CO 80303

ABSTRACT

An intercomparison of optical disc birefringence measurements using commercial instrumentation found in manufacturing settings showed significant measurement variation. We discuss possible sources of variation in these measurements, including changes in disc properties and coherence effects. We describe specific measurement errors related to deviations from circular input polarization in one class of polarimetric instruments. Efforts to mitigate measurement errors, such as the development of calibration artifacts, are discussed.

Keywords: birefringence, metrology, optical disc, polarimetry, retardance

1. INTRODUCTION

Birefringence in optical disc substrates can affect playback performance in several ways [1]. Double refraction in the disc substrate can degrade the focused spot and increase playback jitter, crosstalk, and tracking error. In polarization sensitive optical heads, birefringence may change the beam's polarization state and decrease the signal-to-noise ratio. To control these effects, media formats require that the disc retardance be kept within specific ranges. For example, the specification for compact disc requires that double-pass retardance be less than 100 nm at a wavelength of 780 nm [2].

When discs are injection molded, in-plane birefringence results from nonuniform cooling of the polymer flow as the mold fills. The polymer that contacts the cooler mold walls solidifies more quickly than that in the center, and the resulting shrinkage of the internal plastic creates stresses that cause birefringence [3]. Vertical birefringence arises from an anisotropic molecular polarizability that is observed in the bulk because the rigid polymer preferentially orients with the long axis within the plane of the disc. Cycle time is a key component of production cost, and replicators balance birefringence with molding time to maximize product throughput and economically meet this specification. Disc birefringence measurements are routinely made to ensure disc quality, and replicators often rely on a variety of commercial polarimetric instruments available from several manufacturers.

Many users, however, have observed significant measurement variation when using these instruments. To quantify the reliability of these tools, NIST performed a round robin intercomparison study with the Optical Disc Manufacturing Association (ODMA). The results show that measurement variation among instruments is indeed remarkably large and improvement is needed.

2. INTERCOMPARISON MEASUREMENTS

The round robin comprised eight instruments representing four equipment manufactures (and seven models). A set of 20 discs (18 injection molded polycarbonate discs, a nominally 100 nm retardance strained plastic disc "T", and a low retardance glass disc "S") was measured on each instrument. Participants measured the same location on each disc; an azimuthal angle was marked with lines at the inner and outer data radii, and retardance was measured at a specified radius between these lines. The measurement radius was chosen after making preliminary measurements so that a wide range of retardance would be represented by the disc set. Participants also measured the maximum, minimum, and average retardance of a track defined by the specified radius, and each measurement was made five times. Temperature, instrument wavelength and incidence angle were reported, and data were sent to NIST for analysis to ensure the anonymity of participants.

3. MEASUREMENT VARIATION

The absolute values of the reported single-point measurements are shown in Figure 1. Minimum, maximum, and average measurements over a complete circumference showed similarly large variations. For most of the discs, including disc T, which is often used for instrument calibration, the measurement range is a significant fraction of the maximum allowed retardance.

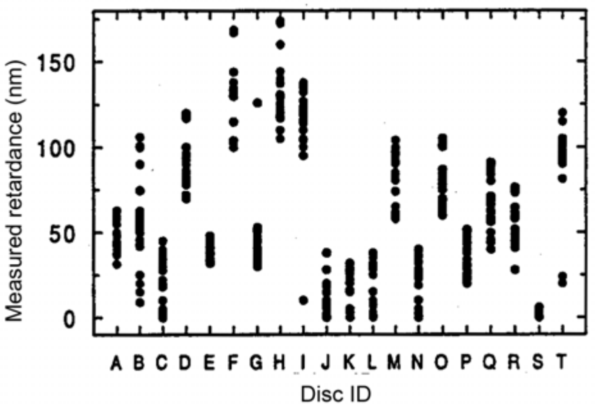

Figure 1. Round robin retardance measurements.

While indicative of the optical disc measurement uncertainty faced by replicators, we cannot estimate the contribution of instrumental uncertainty from these data. Polycarbonate disc retardance can be influenced by environment, and optical disc measurements can vary with incidence angle and other experimental variables. These factors may have contributed to the reported measurement range. To estimate these contributions we selected several samples for additional measurements to estimate the magnitude of disc variation.

We measured retardance using a rotating analyzer polarimeter (Figure 2). In our system, circular polarization is incident on the disc, and the reflected beam is analyzed at ~100 Hz and detected. Incidence angle can be varied; for normal incidence a low-retardance beamsplitter [4] is inserted after the compensator to redirect the reflected light to the analyzer. Circular polarization was precisely set by removing the disc, placing the rotating polarizer in the beam path, and analyzing the polarization exiting the compensator. Retardance $\delta = \sin^{-1}(2^{\frac{1}{2}} V_{ac}/V_{DC})$, where V_{ac} is the RMS detector signal from a lock-in amplifier synchronized with the analyzer rotation, and V_{DC} is the DC photodetector signal. Uncertainty is less than 3 nm and is predominantly due to compensator spatial variation and scale-factor differences between the AC and DC voltmeters. Accuracy was verified by measuring zero-order waveplates with this instrument and comparing to measurements made using polarimeters that we have previously characterized and shown to have less than 0.1° uncertainty. [5].

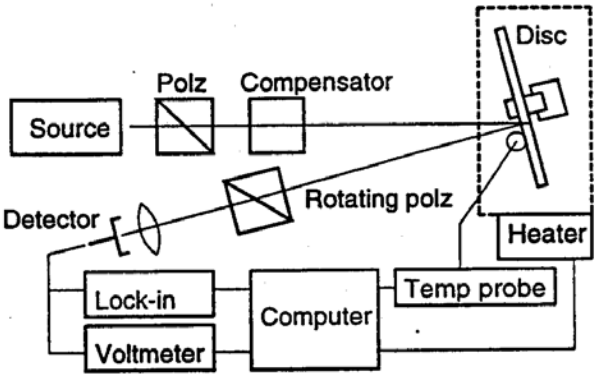

Figure 2. Polarimeter used to measure optical disc retardance.

Because in-plane birefringence arises from stress in the disc, temperature changes that induce stress through differential thermal expansion may be significant. For example, on-line testing of replicated discs shows very large variation because the rapid cooling after replication creates time-varying strains that modify birefringence. Though we observed no correlation between temperature and retardance in the data reported by participants, we performed several measurements to ascertain the magnitude of temperature-induced changes. We measured the retardance of discs while heated and cooled in an insulated chamber, and observed that retardance changes depend on the rate of heating and cooling rather than the equilibrium temperature. Figure 3 shows retardance changes for temperature variations (up to

0.6 °C/min) greater than that encountered during round robin measurements. As Figure 4 shows lower rates of temperature change yield smaller retardance variation, with retardance variation appreciable only at turning points. Discs held at equilibrium temperatures 10 °C or more above room temperature do not exhibit significant retardance changes. Since the round robin procedure required that the discs be allowed to reach thermal equilibrium for 24 hours before testing, the retardance variations due to temperature changes should be considerably smaller and should not have contributed to the intercomparison variation.

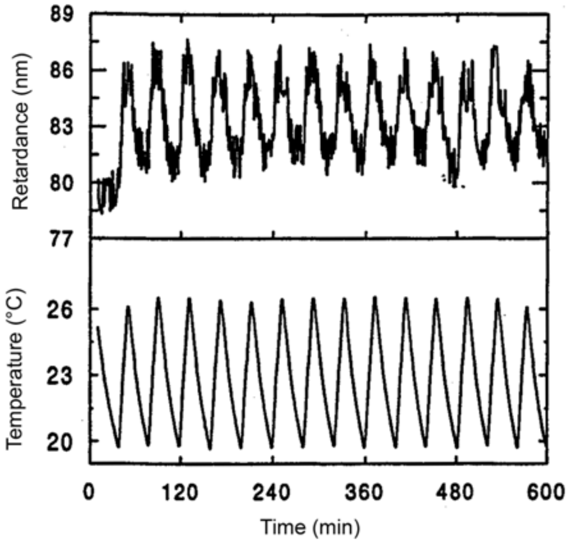

Figure 3. Retardance change with temperature shows a 10nm range and a 2nm standard deviation.

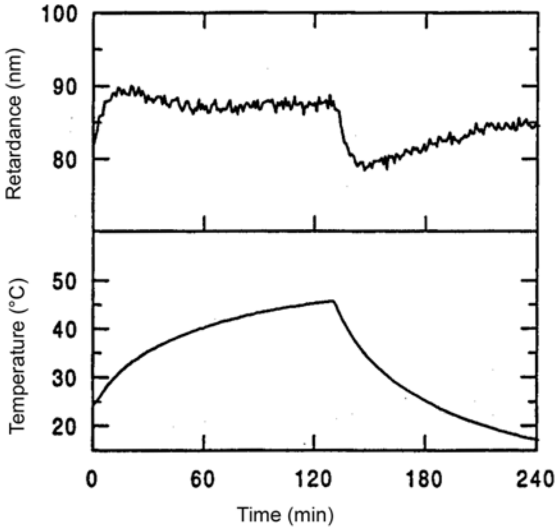

Figure 4. Retardance change with temperature shows a 12 nm range and 3 nm standard deviation.

We measured retardance over the range of incidence angles used in the participating instruments and found a ≤ 7 nm variation. More importantly, we found no correlation between retardance and instrument incidence angle in the round robin data. We also estimated the spatial variation by measuring retardance at numerous positions (on a square grid with 1 mm centers) within a 4 mm radius about the specified location. These retardance variations measured in two discs are listed in Table 1.

Table 1. Experimental variation of disc retardance compared to round robin ranges

	Disc "O"		Disc "M"	
parameter	σ (nm)	range (nm)	σ (nm)	range (nm)
incidence angle		6		7
spatial variation	6	22	3	21
round robin results	11	45	16	46

Comparison of disc measurements made at NIST before and after the round robin using an interferometric retardance measurement system [4] showed < 6 nm change, suggesting that shipping and handling was not a factor. Clearly, only a fraction of the round robin range can be attributed to disc variations, and instrumental uncertainty appears to make a significant contribution.

4. ERROR SOURCES AND MITIGATION

At least two efforts are underway to improve this measurement situation. Currently, ODMA and NIST are repeating the round robin using a waveplate-based artifact. Waveplates can possess much better stability than polycarbonate discs, and this second set of measurements will provide a direct assessment of instrument variation. If successful, NIST will develop calibration artifacts based on this design.

Because standardized measurements and calibrations have not been adopted, the diversity of methods used by industry contributes to variation. For example, incidence angles vary among the designs, so that vertical birefringence contributions differ among the measurements. For intercomparison purposes we can independently measure and quantify this contribution, but correction is impossible for an arbitrary disc measurement. Only recently, as part of DVD standardization efforts, have specific birefringence measurements been proposed.

One proposal suggests analyzing the reflection of a circularly polarized beam incident on a disc by rotating a polarizer and measuring transmission modulation. This is similar to the system shown in Figure 2, though modulation is measured using manual rotation and DC voltage measurement. Typically, circular polarization is created using a linear polarizer and quarterwave plate retarder, but retarder accuracy is critical since these variations directly contribute to measurement error. Previous work by NIST has shown that measurements of commercial quarterwave retarders may have retardance error ranges of 5 % or more [6], so it is likely that this error source is significant.

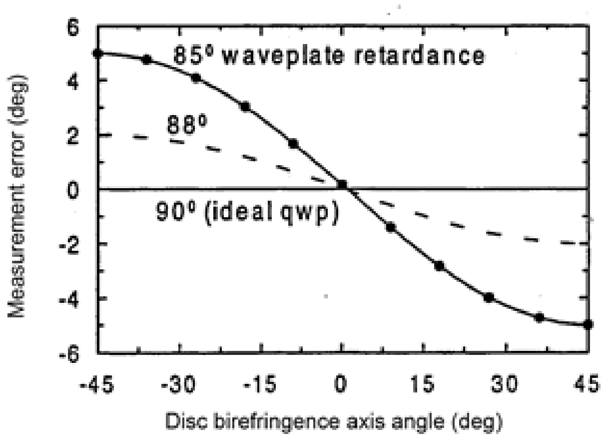

Figure 5. Measurement error for due to biasing quarterwave plate (qwp) error for disc with 55° retardance (or 99 nm at 650 nm wavelength).

Some have suggested that input polarization error can be directly measured and simply subtracted from the measurement value as part of a calibration. We have modeled the system in Figure 2 using Jones calculus and find that simple subtraction of input polarization errors is insufficient. Analysis shows that the magnitude and sign of the correction depends on the orientation of disc birefringence axes (Figure 5). We have verified this model by measuring retardance at various input polarizations and disc orientations and find excellent agreement. Error is minimized when the disc retardance axes are coincident with the orientation of the linear polarizer placed before the compensator (or quarterwave plate) but this alignment requirement may be undesirable in manufacturing environments that demand measurement simplicity. Thus, measurements that do not rely on a particular disc orientation must specify allowed tolerances on the input polarization state (and require an accurate waveplate or an adjustable retarder) rather than attempting to correct for variation from circular polarization.

The type of optical source used for measurement may also play a role in measurement variation. If the coherence length of the measurement source is not much smaller than the disc's optical thickness, the effect of coherent multiple reflections may be significant [5]. In this case, the measured retardance depends on the front surface and data layer reflectances, and is more sensitive to wavelength X and optical thickness of the disc than in the incoherent case. If the reflecting surfaces are sufficiently parallel, measured retardance varies about the true material value as the optical thickness varies by ±A./2. Net reflectance also changes, as for a low-finesse etalon, and may contribute additional uncertainty if intensity-based birefringence measurements are used. If the disc flatness is more than several λ over the measurement beam area, the spatial variation of retardance is averaged and the error decreases.

However, optical discs often exhibit sufficient flatness over millimeter distances to change retardance by 20 % or more if a single-longitudinal mode laser diode is used for measurement. Measurements made with a broadband source, such as a superluminescent diode, show negligible coherence effects. Multi-mode laser diodes may show reduced effects, but this depends on mode structure and disc thickness. Typical coherence functions for these lasers exhibit a periodic oscillation with optical path difference, and some disc optical path lengths may correspond to a delay with high coherence. Both uncoated and anti-reflection coated waveplates will be measured in our next round robin to estimate the magnitude of this error source.

ACKNOWLEDGMENTS

This work was first reported at in a paper with the same title at the joint International Symposium on Optical Memory and Optical Data Storage 1999 in Kauai Hawaii, July 12-15, 1999. We authors thank Al Yaniero and Karl Schneck of ODMA for help with the round robin organization. This manuscript is work of the US Government and is not subject to copyright.

REFERENCES

1. B.E. Bemaki and M. Mansuripur, "Investigation of substrate birefringence effects on optical-disk performance," Applied Optics 32 (1993) p. 6547.
2. "Compact disc digital audio system," IEC-908, International Electrotechnical Commission (Geneva, Switzerland, 1987).
3. C.R. Sandstrom, "Optical disc substrate technology," in Optical Data Storage, Vol. 8, OSA Technical Digest Series (Optical Society of America, Wash., D.C., 1998) p. 62.
4. K.B. Rochford and C.M. Wang, "Accurate interferometric retardance measurements," Appl. Opt. 36 (1996) p. 6473.
5. K.B. Rochford, A.H. Rose, P.A. Williams, LG. Clarke, P.D. Hale, and G.W. Day, "Design and performance of a stable linear retarder," Appl. Opt. 36 (1996) p. 6458.
6. K.B. Rochford, A.H. Rose, and C.M. Wang, "NIST study investigates retardance uncertainty," Laser Focus World (May 1997) p.223.