MODULATION OF THE READBACK SIGNAL DUE TO SUBSTRATE BIREFRINGENCE

Y. WATANABE, A. OHYA, M. KOMATSU, Y. KISAKA, H. YOSHIDA, Y. KOBAYASHI, T. YOSHITOMI, and M. HASUO
Mitsubishi Chemical Industries, Research Center, Midori-ku, Yokohama 227, Japan

ABSTRACT
The effects of the substrate birefringence on the readback signal envelope of the magneto-optical disk are studied by a numerical model and model experiments. The envelope modulation of the RF signal amplitude is confirmed to be reduced by several percents by the adjustment of the conditions in the dynamic test. However, a low frequency noise is caused by local variation of the birefringence of the substrate. It is suggested that the conventional birefringence model for a typical plastic substrate might not be sufficient and a new model is proposed.

1. INTRODUCTION
Injection molded polycarbonate (PC) substrate is one of the most suitable substrates for the magneto-optical disk for commercial use. Discussions have been held on the effects of the substrate birefringence on the Carrier to Noise Ratio (CNR) [1,2,3]. Now it is well known that the birefringence of the ordinary PC substrate has little effect on the CNR of the magneto-optical disk when using a differential detection system. The envelope of the readback signal in the PC substrate disk was usually found to have a much greater modulation than that of disks with a glass substrate. The modulation was divided into two categories in accordance with its source. (1) the modulation of the RF signal amplitude, and (2) the modulation of low frequency noise. The former corresponds to the local variation at the carrier level and so was not removed by a high pass filter. The latter corresponds to the meandering of the signal envelope which contributed to the jitter and was regarded as a local variation in DC bias, effectively removed by a high pass filter.

We measured the distribution of birefringence on several PC disks and the signal envelope of those disks. We then investigated these modulations through numerical models and model experiments. The Jones matrix method was applied to a simplified optical system, in which the substrate birefringence at a point was represented by a single, biaxial, refractive ellipsoid [4].

2. EXPERIMENTAL
The magneto-optical disks covered with a thin film of TbFeCo were prepared with several disk substrates by a sputtering method. The envelopes of these disks were measured by a dynamic tester with a PIN-differential detection system. The conditions for readout were as follows: read power = 0.8 mW, carrier frequency = 0.5 or 1.0 MHz, and a constant linear velocity of 4 m/s.

Static Model experiments were performed for the reflection and transmission cases. The angle of orientation for the maximum electric field intensity (i.e. polarization direction) was determined through a system which is similar to the measurement system for the Kerr rotation (Fig.1). The HeNe laser (beam wave length=633nm) was first linearly polarized (PO), by passing it through the substrate; then, the transmitted or reflected beam was modulated by a Faraday cell. The beam was finally detected by a photomultiplier after its passage through an analyzer (AO). The outputs of the photomultiplier and the Faraday cell were connected to a lock-in amplifier.

3. NUMERICAL MODEL
The numerical model used is based on the well-known Jones matrix formula. The expression of birefringence for the arbitrary incident direction of parallel beam \( m = (\sin \theta \cos \omega, \sin \theta \sin \omega, \cos \theta) \) is given with two constraints

\[
(m,E) = 0, \quad E_z (E_x, E_y, E_z) \quad (2) \quad E_x^2/N_1^2 + E_y^2/N_2^2 + E_z^2/N_3^2 = 1 \quad (3)
\]

where the z axis is assumed to lie perpendicular to the substrate plane.

Under these constraints, the \( E \) for maximum and minimum \( (E^1) \) is calculated. The difference between these \( E \)'s is the magnitude of birefringence \( \Delta N \) and the value of \( E \) gives the direction for the principal axis of the refractive ellipse (OPARE) for
a given incident beam direction (DPARE coincides with the direction of N1 and N2 for vertical incidence). If we express N1, N2 and N3 as N1=No, N2=No+\Delta N2 and N3=No+\Delta N3 respectively, we can assume that No>>\Delta N>>\Delta N2>>\Delta N3 without losing the generality. The value of \Delta N is known to be large and is essential in the birefringence of the PC substrate[5]. We obtain an approximate expression for the magnitude of birefringence, by retaining the first order in \Delta N3 and \Delta N2.

\[ N=N(c)-N(c') \]

\[ = No + (\Delta N2 (\sin^2 \omega + 2c \sin \omega \cos \omega + \cos^2 \omega) + \Delta N3 \tan^2 \omega)/(g + g') \]

\[ g = 1 + \tan \theta \]

\[ u = (\Delta N2/\Delta N3 \tan^2 \theta - \cos 2\omega - \cos^2 \omega \tan^2 \theta)/\sin 2\theta ; No = 1.580. \quad (4) \]

The Jones matrix expression of polarization for one beam pass in a converging beam is

\[ T_q = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \quad T_a = \begin{bmatrix} -\sin \theta & \cos \theta \\ \cos \theta & \sin \theta \end{bmatrix}, \quad T = \begin{bmatrix} \exp(i\alpha/2) & 0 \\ 0 & \exp(i\alpha/2) \end{bmatrix}. \quad (5) \]

where \( \alpha = \) retardation (single pass) calculated from (4). \( q = \) APAP (angle between the DPARE (calculated in (4)) and the polarization direction), and \( rx, ry = \) complex reflectivity for the Kerr rotation and the Kerr ellipticity. Using the equation (5) the intensity of the beam after passing through analyzer is given by

\[ IO = (1+\sin(2\alpha)\sin^2\theta)^{1/2}. \quad (6) \]

Corresponding to equation (6), the rotation of the polarization plane due to birefringence is expressed by a complex function of \( q \) and \( a \) for which exactness was checked for the single crystals (quartz). In the same manner the beam intensities through the analyzer were calculated for two different values of the Kerr angle (= \( 8k \) and \( -8k \)). The difference between these intensities gives the RF signal amplitude.

For the converging beam, we integrate the physical quantities (e.g. RF signal amplitude) for each beam pass over all beam passes, weighting them with beam intensity for the given NA and the initial distribution of the intensities. In the integration, the sensitivity was assumed to be constant on the entire detector plane.

In our calculations, the reflectivities of the magnetic layer for S waves and P waves were assumed to be equal, even for non-vertical incidence; and the dependence of transmissivities of PC and the lens on the polarization (S, P wave) was considered only for the incident beam. The differences between beam passes in the PC due to birefringence were also omitted.

4. RESULTS AND DISCUSSION

Figure 2 shows an example of the readback signal envelope (picture) and the corresponding distribution of in-plane retardation measured in double pass (\( \Delta N \): circle). It also shows the direction of the principal axis (DPARE) (\( \Delta N \): square). The upper curve shows the envelope measured without a high pass filter; and the lower curve shows the envelope measured with a high pass filter (\( fc = 5 \text{ KHz} \)). The \( \phi \) denotes the azimuthal angle along groove on the substrate. Figure 1 shows how low frequency noise (meandering of the envelope) was removed by the high pass filter and how variation of envelope width was maintained. The variation of the envelope width, that is the RF signal amplitude, was observed to be between ±5% and ±20%.

In order to estimate the limit of the birefringence contribution to the RF signal amplitude modulation, we calculated the modulation amplitude due to the birefringence for given PC substrates directly. In this way, the dependence of signal intensity on the retardation (\( \Delta N \)) and the DPARE were also calculated.

Figure 3 shows how the RF signal intensity relates to the intensity for no birefringence in the case of parallel beams. Numerical values of \( rx = (0.126, -0.896) \) and \( ry = (-0.0055, -0.003) \) were used in the equation (5), corresponding to the TbFeCo single layer. The signal amplitude degradation depends greatly on the value of \( \Delta N \), and little on the value of \( q \) (DPARE), even for \( \Delta N = 100 \text{nm} \). This weak dependence of the signal amplitude on the angle \( q \) comes from the small Kerr ellipticity.

Before the above results were applied to the converging beam, the birefringence of typical injection molded PCs was measured. Figures 4a and 4b show the dependence of \( \Delta N \) of two different PC disks on the incident angle (\( \theta \)) of laser beam (HeNe 633nm), where \( \Delta N \) is defined for a single pass and the angle \( \theta \) is defined in air. The dark squares, the light
squares and the triangles correspond to \( \Delta N \) at different locations (radius) on the substrate. The value of \( \Delta N \) in the plane (\( \Delta N_{\parallel} \)) was confirmed to vary on the disk substrate. On the other hand, the value of \( \Delta N_{\perp} \) was found to be almost constant on each disk substrate. The solid curve shows the calculation (eq. (4)) of \( \Delta N \) for fixed \( \Delta N_{\perp} \) in each substrate. The agreement of the calculations with the experimental data indicates constancy of \( \Delta N_{\perp} \) in each disk.

Figure 5a shows the calculated dependence of RF signal intensity for a converging beam of a circular beam shape on \( \Delta N_{\perp} \) (\( \Delta N_{\parallel} \) in-plane) for a fixed effective NA=0.4. The calculated RF intensity profiles on the detector are shown in the circles in Fig.5a for \( \Delta N_{\perp}=0 \) (left), \( \neq 0 \) (right). The degree of darkness corresponds to the degree of degradation. The degradation of the RF signal was estimated to be about 1 dB or less for ordinary PC substrates, depending on the values of \( \Delta N_{\perp} \) and \( \Delta N_{\parallel} \). The variation of the RF signal intensity, directly related to birefringence, was estimated to be less than \( \pm 2\% \) for ordinary PC. This is because the degradation of the RF signal amplitude was largely due to the \( \Delta N_{\perp} \) which was nearly constant.

Figure 5b shows the same plot as Fig.5a for elliptical beam shape (effective NA=0.46). In this case the modulation was estimated to be less than \( \pm 3\% \). These results were confirmed experimentally by the dynamic test. The total modulation of the RF signal amplitude was observed to be from \( \pm 3\% \) to \( \pm 5\% \). If the cross-talk of the signal was removed and the servo-system was properly adjusted to the PC substrates.

The other type of modulation of the signal envelope (low frequency noise) is shown in Fig.2 (upper curve). The peaks in the envelope and in the variation of the DPAPE(\( \Delta b \)) were seen to coincide in many cases. Unfortunately, the quantitative agreement between these modulations and the variations of the envelope, calculated by eq. (6) for vertical incidence of the parallel beam, was very poor. At first we thought that the discrepancy might be removed, if we calculated eq. (6) for converging beams and thus take \( \Delta N_{\perp} \) into consideration. However, we found that the value of \( \Delta N_{\perp} \) had little effect on this modulation.

Figure 6 illustrates this fact and shows the distribution of laser intensity (DC) on the detector. When the open angle of the analyzer is 45° from the extinction position. The shaded area, the dark area and light area have standard beam intensities, less than 90% of the standard intensity and more than 110% of the standard intensity, respectively. (The circle represents the detector plane.)

The parameters for each are as follows: \( \Delta N_{\perp}=0 \) for left circle, \( \Delta N_{\perp}=20 \) nm for the others. \( \Delta N_{\perp}=800 \) nm for all, the angle between the initial polarization direction and the direction of the N1 axis=20° for the right circle, 0° for the others. The
differences in the total beam intensity integrated over each circle correspond to the differences of the central position of the signal envelope. This difference was calculated to be almost the same as that for vertical incidence of parallel beams. This is due to the cancellation of contributions made by the dark region by those of the light region where the angle is most effective.

Further, Static model experiments were performed (reflection case) and then results were compared with the calculations already made. Figure 7 shows the distribution of rotation angles of the polarization plane (rotation due to birefringence of the PC substrate) for two PC disks. The incident angle of the parallel beams was less than 8° in air of the experiments. These results agree roughly with the calculations but not exactly. Therefore, we reexamined the model for the birefringence of the PC substrate. Relationships between the basic quantities, which are easily calculated and checked in the PC substrate and in an ideal birefringence material such as quartz, were examined experimentally (the case. Fig. 6). The extinction ratio vs. $\phi$ for a fixed $\Delta N$ (q:APAP) and the rotation angle vs. $\phi$ for a fixed $\Delta N$ were investigated for parallel beams.

Figure 8 shows the dependence of rotation of the polarization plane from the initial direction on the angle $\phi$ (i.e. the angle of the polarizer). The calculations based on a conventional model for the PC birefringence (single biaxial refractive ellipsoid) (dashed line) differed from the experimental results (solid line). In the new model where inhomogeneity of birefringence ($\Delta N2$) in the direction vertical to the substrate plane was included (solid line), the results agreed with the data. The conventional model could not explain 2 basic points in the experiments: 1) why the rotation angle was much larger than expected, or 2) why the sign of the rotation angle was always negative for all $\phi$ angles.

This effect was calculated to be most effective when the distribution of the birefringence was asymmetrical along the direction of light propagation (i.e. for the case of transmission this condition can be more easily satisfied than the parallel reflection case.) The details of the model and the calculation will be reported later. (The introduction of the inhomogeneity does not affect the former calculation of signal amplitude, because the signal amplitude is primarily affected by the total retardation.)

The birefringence of the PC may seem very complicated, as is its relation with the condition for the injection-molding. However, it was possible to obtain a disk with a flat envelope without using the high pass filter (Fig. 9). Mold condition for the disk is different from that in Fig. 1.

5. CONCLUSION

The birefringence of the PC was verified to affect only slightly the RF signal envelope modulation owing to the constancy of $\Delta N2$ in each PC disk. However, a quantitative explanation of the low frequency noise by a simplified conventional model appears insufficient and the importance of inhomogeneity in the in-plane birefringence ($\Delta N2$) in the vertical direction is suggested.

The authors would like to acknowledge Mr. T. Kurata the director of the material science division for his continuous encouragement.

REFERENCES