CRITICAL ISSUES IN THE CHARACTERIZATION OF MAGNETO-OPTIC MEDIA (Invited)

J.E. HURST, Jr., D. CHENG and C.R. DAVIS

IBM Research Division, Almaden Research Center, MS K67/802, 650 Harry Road, San Jose Ca. 95120, USA

Abstract—Applications of time domain testing techniques which permit characterization of the media contributions to the performance of an MO channel are discussed; including both small (μm) scale phenomena appropriate to recording physics studies, and, larger (mm) scale phenomena appropriate to disk mapping and uniformity studies. Recording physics studies are described wherein the components of timing shifts in the channel due to properties of the media are characterized in terms of thermal, optical, and, magnetic crosstalk contributions. In this context laser power precompensation of edge positions is characterized. Timing jitters in the channel due to the properties of the media are characterized in terms of the noise contributions which limit performance, such as media and writing noises which scale linearly in the read power. Disk mapping studies are described wherein a software bit-error rate mapping technique is used to measure and characterize media defects.

KEYWORDS: MAGNETO-OPTIC RECORDING, MEDIA CHARACTERIZATION

INTRODUCTION AND EXPERIMENTAL

The characterization techniques used to evaluate the MO recording process and the associated media must keep pace with the ever evolving and increasingly complex MO recording technologies. One such direction in improved media characterization has been the increasing importance of time-domain testing, both of media to characterize performance and of the recording process in general to evaluate/compare technologies. We describe below results from two systems which run the gambit from high speed disk characterization to slower, albeit more detailed, recording physics studies.

The first system utilizes a straightforward approach to capturing and analyzing the recorded information from the media, i.e. a fast transient digitizer. Current commercial units allow digitization rates up to 1 GHz (8 bit resolution) and memory depths of over 4MByte which corresponds to over 4 mS of recorded data; insufficient to handle a complete data track (25–35 mS) but more than adequate to study individual timing shifts and jitters. The layout of a system utilizing this concept is shown in Fig. 1a. We have developed such a system operating in the red at 648 nm (Kr⁺ ion laser) and in the blue at 488 nm (Ar⁺ ion laser) which uses a commercially available fast AO modulator and a 200 MHz AFG (LeCroy 9109) as the write channel and a 200 MHz transient recorder (LeCroy TR8828D) as the read channel.

This arrangement offers several advantages when high speed characterization of the entire disk surface is not the objective. First, because both the write channel (by way of an arbitrary function generator = AFG) and the entire read channel are implemented in software, the maximum in flexibility is provided. This allows for rapid testing of alternative write algorithms, compensation schemes, edge detectors, etc., thereby obviating the need for hardware development at the early stages of testing. Second, because the data is captured, playback can occur through the AFG directly to the read channel, eliminating the media/test stand and allowing for faster hardware development. Finally, error capture in this case

is trivial, the task being reduced to finding the errors!

Figure 1: Schematic of media test configuration for a) recording physics/edge analysis, and, b) high speed disk mapping/edge analysis.

In contrast to the above applications, when high speed characterization of the disk surface is desired some degree of flexibility must be sacrificed to increased the data acquisition times. This usually involves placing most of the read channel into hardware. An excellent example of such a system utilizing a custom designed time-interval-digitizer (TID) having 20 pS resolution has been described previously[1]. This device combines hardware sectoring and histogramming capability with a shared memory architecture (eliminating the need for data transfer to the controlling computer) to achieve very high speed disk mapping capability. A system utilizing

this concept is shown in Figure 1b where the implementation of software bit-error rate (BER) is shown. These studies are carried out with an 830 nm diode laser using a 0.6NA objective.

RESULTS AND DISCUSSION

Recording Physics Studies: Timing Shifts

Characterization of the thermomagnetic recording process at the scale of the domain sizes of current interest, i.e. 0.3 – 10 microns in length, naturally leads to the consideration of four phenomena: thermal and magnetic crosstalks which could alter the position of the domain edge during writing, optical crosstalk which could alter the apparent position of the domain edge during readback, and, noise which could alter the domain edge position during both writing and readback depending on the nature of the noise and its source. Of course during readback, noise can be characterized in the channel by its time domain equivalent, jitter. The presence of thermal and magnetic crosstalk are especially detrimental because such processes are usually referred to as "non-linear" meaning that the readback waveform can no longer be expressed as a linear superposition of the single domain responses. In fact, in recording applications the term refers to a much more stringent condition, namely, that the readback waveform can be expressed as a linear superposition of the isolated edge response and its time reversed compliment. These "non-linear" processes, unlike optical crosstalk which is by its very nature is a linear process, cannot be corrected by an equalizer in the readback channel and therefore degrades channel performance.

Fortunately one of these phenomena, magnetic crosstalk, can be almost completely eliminated with appropriate choice of composition in the TbFeCo system. Thermal and optical crosstalks on the other hand are especially troublesome for higher performance PWM applications at high density and data rates and the separation/quantification of these factors can be difficult. A technique for measuring the relative contribution of these effects under nominal recording conditions is described below.

A block of domains is written which includes a group of high frequency marks/gaps followed by groups of lower frequency marks/gaps of particular interest. This is indicated in Figure 2. Here high frequency refers to marks/gaps which correspond to the shortest allowed by the code, i.e. for a 1/2(2,7) code at 4 MByte/sec data rate this corresponds to a code clock of $T_c = 15$ nS or a minimum mark/gap of $3T_c = 45$ nS. Low frequency refers to any of the other mark/gap lengths allowed by the code, i.e. $4T_c$ through $8T_c$ for the example given above. The length of the initial high frequency mark/gap group is sufficient to ensure that the media has reached a thermal "steady state" wherein the mark size is no longer changing. In the examples described here, which were all recorded on a typical quadrilayer disk structure utilizing an Al cooling layer, we have found that ten mark/gap combinations (labeled 1 – 10 in Figure 2) are sufficient to meet this criterion. This group is followed successively by a group of low frequency marks separated by low frequency gaps, a group of low frequency marks with high frequency gaps, and, a group of high frequency marks with low frequency gaps. The entire block is repeated many times around the track with each block separated

Figure 2: Sequence of written domains used when measuring the relative effects of thermal and optical crosstalk. The numbers below each domain are reference numbers used in the text.

by the lowest frequency gap. The laser power/pulse width is adjusted so as to ensure that the high frequency carrier readback width is correct. The degree of thermal and optical crosstalk depends on the actual size of the marks/gaps, i.e. their linear density. The results described here were recorded using a 0.6NA objective and 647nm (Kr+ laser) at 42 kbpi which for a 1/2(2,7) code at 4 MByte/sec corresponds to a media velocity of 20 m/s.

Once the domain pattern has been recorded on the media, readback and analysis are performed using the software channel described above. For the examples described here the edge detector consisted of a maximum slope detector with the usual level and alternating leading/trailing edge qualifiers. Additionally, a block verify has been added which rejects unreadable blocks caused by hard errors (media defects). An important consideration in performing the measurement is to ensure there is minimal filtering in the channel as filtering will alter the measured edge positions. Indeed, in these experiments filtering was added only to the extent that the measured edge positions did not move. This is because we are interested in the position of the domain edges on the media rather than optimizing the performance of the channel by decreasing noise. The results of the measurement of several hundred blocks of recorded domains (measured sequentially during a single disk rotation) are the mean position and jitter associated with each domain edge, or alternatively, the mean size and jitter associated with each domain.

In order to interpret these results as errors in the positions of the different edges it is necessary to choose a reference wherein the desired position of each edge is defined. We take as the reference frame the somewhat arbitrary choice of domain #8 (c.f. Figure 2) since, by the nature of the writing process described above, this domain was written at a quasi-steady state thermal distribution in the media and the laser power was chosen so as to make the high frequency pattern read correctly. Therefore, by virtue of the calibration process, we expect no errors on these edges and can define both the frequency of the code clock, $1/T_c$, and its phase. Note that this "clock" is not equivalent to that derived using the usual phase-locked loop channel which would distribute the phase error (or edge position errors) over many

edges. Instead we desire the errors to be measured relative to a "correct" mark. The results of this measurement are shown for domain #10 and #1 in Figures 3-4, respectively.

Figure 3: Measured timing errors for domain #10 (c.f. Figure 2) and the associated optical and thermal contributions vs. laser power used to write domain #10 relative to the laser power which gives zero timing errors for a high frequency carrier.

Figure 4: Measured timing errors for domain #1 (c.f. Figure 2) and the associated optical and thermal contributions vs. laser power used to write domain #1 relative to the laser power which gives zero timing errors for a high frequency carrier.

First we consider the edge shifts for domain #10 shown in Figure 3 since this demonstrates the simplest type of edge shift; namely, one due purely to optical crosstalk effects. Because of the calibration procedure used to write the high frequency carrier we expect no timing errors on the leading edge of this domain whereas the trailing edge could have timing errors resulting from the lack of a subsequent leading edge where it would normally occur in the high frequency carrier. This is precisely what is observed in Figure 3 for relative power equal to unity. The error on the trailing edge of domain #10 due to optical crosstalk under these conditions is about 1.2 nS or 16% of the clock half window, $T_c/2$. Note that at 20 m/s this corresponds to a shift of the domain edge of only 24 nm.

The shift of the domain edge toward longer times is consistent with a simple optical readback model of optical crosstalk wherein the observed signal is the overlap of a gaussian laser spot with a series of circular domains. When this model is coupled with a maximum slope edge detector, optical crosstalk results in the movement of the detected domain edge away from the center of interaction; i.e. the domain size appears to decrease. The magnitude of the error depends on the ratio of the characteristic bit length to the sigma of the gaussian spot, $T_c V / \sigma$. Here, the characteristic bit length is the distance traversed by the media during one code clock and is given as the product of the code clock and the media velocity, V .

The data of Figure 3 also demonstrates how the detected edges of domain #10 move as the laser power used to write the domain is selectively decreased. This is what would be expected if laser power precompensation were used in an attempt to correct the optical error on the trailing edge. Decreasing laser write power causes the domain to shrink and the leading edge moves to later time while the trailing edge move to earlier time. At some critical power (93.4% of the calibration power in this case) the optical error is equally distributed between the leading and trailing edges and the net error in the domain size is zero. Clearly, power precompensation alone is incapable

Figure 5: Measured timing errors for domain #23 (c.f. Figure 2) and the associated optical and thermal contributions vs. laser power used to write domain #23 relative to the laser power which gives zero timing errors for a high frequency carrier.

of completely correcting even this simple optical error; the best it can achieve is a reduction in the error by about a factor of two. In order to completely correct the error, a phase shift in the domain position of about one half the timing error due to optical crosstalk, or equivalently in the pulse used to write the domain, would be required.

Shown in Figure 4 is the more complicated case of domain #1 where not only is there an optical error on the leading edge but the possibility of a thermal error on both edges as well. The thermal error could be caused by the fact that domain #1 is written after a lowest frequency gap (8 T_c in this case) and some cooling of the media relative to the reference domain #8 may have occurred. The data in Figure 4 however show this thermal effect to be minimal for these conditions and this disk structure and the errors are completely dominated by the optical error on the

leading edge. Again, laser power precompensation can only correct about one half of the optical error. Note that the laser write power which best compensates for the edge errors is lower than the calibrated power; opposite from the expected higher write power which would have been required had thermal effects dominated.

As a final example consider the case of an isolated (separated by lowest frequency, $8T_c$, gaps) high frequency ($3T_c$) mark; c.f. Figure 5 which is data for domain #23 in Figure 2. Now there are errors due to optical crosstalk present on both the leading and trailing edges along with the possibility of thermal errors as well. As indicated by the figure, the optical errors completely dominate under these conditions and, because they are present equally on both edges, it is now possible to completely correct the errors by decreasing laser write power; in this case to 88.9% of the calibration power.

Recording Physics Studies: Timing Jitters

Up to this point we have considered only phenomena which lead primarily to timing shifts in the channel; however timing jitters are as important, if not more, in determining the performance of the system. Timing jitters can arise from a variety of physical phenomena but from the point of view of MO recording we are naturally lead to the distinction between those phenomena which lead to jitters which increase sublinearly in read power in contrast to those which lead to jitters which increase either linearly or superlinearly. This is because system performance (SNR, CNR etc.) can always be improved by increasing read power and desensitizing the media in cases where the jitter scales sublinearly; i.e. there is a trade-off between increased performance and decreased laser power in these cases. Some examples of noise sources which lead to jitters which increase sublinearly in read power are electronic noise ($\propto P_r^0$), shot noise ($\propto \sqrt{P_r}$), some types of laser noise, etc.. Media noise and writing noise are the most common noise sources which scale linearly with P_r . In these cases CNR and SNR are constant independent of laser read power.

A simple experiment which permits this distinction is depicted in Figure 6. A carrier is recorded and the mark lengths of a some number of domains are each measured repeatedly until a suitable level of statistical confidence is achieved. In the data of Figure 6, $2\text{ }\mu\text{m}$ marks/gaps were recorded at 10 m/s at 647 nm/0.6NA and the mark lengths were measured using the experimental setup of Figure 1b without the software BER analysis. The hardware edge detector consisted of a fixed threshold with envelope following and the TID was used to measure the mark lengths of 1000 consecutive marks 1023 times. The same quadrilayer disk structure tested previously for timing shifts was used in these experiments. Shown in Figure 6 are the mean and standard deviation of the 1023 measurements at each domain.

The jitter associated with an individual domain can be derived from Figure 6b and is $1.14\text{ nS} \pm 0.05\text{ nS}$. This represents jitter associated with electronic noise, shot noise, laser noise etc and as such can be made less important relative to the signal level by increasing laser read power (in this case laser noise scales sublinearly with laser power). The jitter associated with errors in the

placement of the domain edges when they were recorded on the disk can be derived from Figure 6a and is 1.77 nS . This is the jitter associated with media and writing noise and as such can be expected to remain constant with increasing read power. The net jitter observed when measuring the mark length is the result of adding these two numbers in quadrature or 2.11 nS . Clearly, for this particular disk the largest contributor to the jitter are the media and writing noises and as such increasing the read power could at best decrease the combined jitter from 2.11 nS to 1.77 nS or about 16%.

Also of interest to note is the spatial dependence of the domain size and jitter. Clearly there are very high frequency modulations in the domain sizes over distances as short as $4\text{ }\mu\text{m}$ (400 nS at 10 m/s). Also present is a rather larger, $150\text{ }\mu\text{m}$, defect around domain #333. This is evident in both the mean domain size in Figure 6a and especially in the jitter values of Figure 6b. Although this defect is not large enough to cause errors in the channel at this linear density; under more stressed conditions the disk would probably fail at this point.

High Speed Disk Bit Error Rate Mapping

In contrast to the recording physics studies described above, when characterization of the thermomagnetic recording process at the scale of the media itself is

Figure 6: (a) Mean , and, (b) standard deviation of the mark length measured for each of 1000 consecutive domains on the media. Also shown is the associated histogram for each variable.

desired, we are naturally lead to the consideration of phenomena more characteristic of the media fabrication process including both substrate and thin film uniformity, optical properties, etc.. Studies at this scale involve large quantities of data as the properties of micron size marks must be measured over large areas (order $10^3 - 10^4$ mm²). The apparatus in Figure 1b and described previously in the context of domain size mapping of MO disks[1] is able to perform these measurements at reasonably high speeds while retaining the flexibility and power associated with software analysis of the domain information. We describe here an extension of this system which allows for BER mapping of the disk surface.

The test consists of writing an arbitrary but known pattern on the disk, reading the domains back via the TID, and, comparing the two in software to locate errors. An example of such a BER map is shown in Figure 7. In this case, a tone pattern was recorded on the disk (quadrilayer structure) from radii 26 – 40 mm at a constant angular velocity of 1650 RPM using an 830 nm laser and 0.6NA lens. At a track pitch of 1.6 μ m this corresponds to some 8750 tracks tested. To measure BER the TID is used in time-ordered mode wherein each time interval (domain or gap length) is sequentially stored in the shared memory. The TID has sufficient memory to store 512K consecutive intervals which corresponds to more than an entire track of 1 micron marks/gaps (65mm radius). Once the intervals for a track are stored, they are compared to the known sequence and errors are located and categorized as to their type, length etc.. For the example shown in Figure 7, the final BER measured over the entire disk surface was 4.53×10^{-3} .

Shown in Figure 8 is a magnified view of the defect located in sector 23 at a radius of about 33mm. This is the BER "image" of a large 1mm defect. The total time to make the BER measurement is about 3.5 seconds/track or about 8.5 hrs. for this measurement which represents complete testing of 5.8×10^3 mm² of the disk surface. Most of this time is taken in sorting and analyzing the errors by type and subsequently recovering and/or resynchronizing. Of course the test could be made much faster by implementing this functionality in hardware, as is the case for a standard hardware BER tester, although considerable flexibility is usually lost in the process. By retaining the analysis portion of the system in software, it is possible to analyze the errors/defects in detail.

SUMMARY

In summary, we have demonstrated how time domain testing can be used to characterize the performance of MO media in terms of contributions to channel errors caused by timing shifts and jitter. Timing shifts were categorized in terms of optical, thermal, and magnetic crosstalk. Clearly, this analysis can be extended to include the evaluation of various channel parameters such as codes, writing algorithms, etc. A specific example demonstrated in this paper was the use of laser power precompensation wherein the laser power used to write a domain is a function of its thermal prehistory (thermal crosstalk). It was shown that this technique by itself can at best correct only one half the edge timing errors in cases where the error is predominately on only one edge of the domain and in essence spreads the error over both the domain edges. A time shift is required to

Figure 7: BER map of a typical quadrilayer disk. Dark areas represent locations where an error was detected. The ID is 26mm while the OD is 40mm covering some 8750 tracks. The numbers at the OD are sector IDs.

Figure 8: Magnified BER "image" of the defect located in Sector 23 at a radius of 33mm in Figure 8.

correct the remaining error. Timing jitters in the channel were discussed in terms of their equivalent noise sources and the scaling of these sources with the laser power used to read the domains. Specifically, the contribution to the measured jitter from media and writing noises was measured and found to be the dominant source of jitter for the particular disk measured. This was important because these noise sources scale linearly with the read power and as such no improvement in SNR can be realized by increasing the read power and desensitizing the disk. Finally, we have described a fast software BER testing system which permits rapid time domain characterization of the errors in written data on the disk and subsequent mapping of the results into a BER map of

the disk surface showing defects etc. This technique is especially useful in characterizing media defects, uniformity (optical, magnetic, thermal etc.), and, the read channel itself.

REFERENCES

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