TWO-DIMENSIONAL OPTICAL STORAGE

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ABSTRACT

With storage capacities increasing much faster than data rates, fast read-out of content is becoming a bottleneck for the convenient use of optical storage devices. Two-Dimensional Optical Storage (TwoDOS) is a new concept that solves this data-rate problem by using a multi-spot parallel read-out system. In addition, the storage capacity is increased with a factor of at least 2. Using the same read-out physics as in the Blu-ray Disc standard, single layered 12 cm discs with capacities up to 50 GB have been read out successfully at bit-rates as high as 560 Mbit/sec. Basic pillars of TwoDOS are advanced signal processing and disc mastering techniques, and a proper design of the optical path.

1. INTRODUCTION

The capacity of optical storage formats has leaped by a factor of about 70 from CD to dual-layer Blu-ray Disc (DL-BD), whereas the corresponding maximum data-rates have only grown by a factor of 6. As a result, it will take more than 10 times longer to read/write a complete DL-BD disc compared to a CD, see Figure 1. The maximum data-rate is limited by the maximum stable spinning speed of the disc. The above mentioned data-rate problem can be solved by a parallel multi-beam read-out of the information on the disc [1]. In conventional optical storage systems the gain in storage capacity is mainly obtained by reducing the dimensions along the track, i.e. the Channel Bit Length (CBL). In 2D storage [2], however, the extra capacity is mainly obtained by reducing the distance between the individual tracks, i.e. the track pitch (TP), see Figure 2. In that case, conventional 1D detection is not sufficient anymore and for proper dataretrieval advanced 2D signal processing has to be used. By using formats that fully exploit the 2D nature of the optical channel, we achieve at least a factor of 2 increase in storage density. Since our approach is mainly based on signal processing, its gains can be combined with further improvements along the physical roadmap for optical recording.

2. TWODOS CONCEPT

Whereas in conventional optical storage the data is organized in a single spiral, in TwoDOS the channel bits are



Fig. 1. Minimal required time to read-out an entire optical disc at maximum rotation speed.

stored in a broad spiral (or meta-spiral) which consists of multiple, closely spaced bit rows (see Figure 3). The metaspiral is enclosed by an empty guard band, which has a width of less than a single empty bit row. Within the metaspiral, the bit rows are perfectly aligned with respect to each other, i.e. the bits are arranged on a 2D lattice.

Several options exist for the coding of the bits in the 2D meta-spiral. It is possible to use a d=1 Run Length Limited (RLL) Code (like in BD) on a square or hexagonal lattice. Alternatively, the bits may be represented by round pits on a hexagonal, honeycomb-like lattice as shown in Figure 3.

All individual bit rows of the meta-spiral are read out at once, using an array of multiple light spots. Advanced signal processing is used to extract the user-data bit stream from the joint information contained in the multiple signals.

3. SET-UP AND SIGNAL PROCESSING

In order to read out and analyze the disc containing the 2D patterns, an experimental set-up has been constructed. It consists of two parts: (1) the optical set-up which captures the high frequency (HF) waveforms from the disc and (2) the software receiver, which runs on a computer and translates the HF waveforms into the user-data bit stream.



Fig. 2. The capacity of a disc is determined by the Track Pitch (TP, radial density) and the Channel Bit Length (CBL, tangential density). Both are normalized with respect to the 25 GB BD parameters (TP=320 nm, CBL=74.5 nm). By increasing the tangential capacity, and employing 1D signal processing (1D-SP) 35 GB can be reached [3]. For 2D signal processing (2D-SP) on a 2D hexagonal lattice, the radial density is increased whereas the tangential density is even slightly *reduced* in order to reach a capacity of 50 GB.

3.1. Optical Set-Up

To evaluate the TwoDOS storage concept, an optical system using Blu-ray Disc (BD) physics has been designed. The laser wavelength is 405 nm and an objective lens with a Numerical Aperture (NA) of 0.85 is used. The difference with a conventional set-up is the generation of multiple read-out spots by means of a diffraction grating. These spots are focussed onto and aligned with the bit-rows in the meta-spiral, see Figure 3. The HF signals of the different read-out spots are detected by a multi-spot photo-detector IC.

3.2. Software Receiver

After acquisition of the raw HF waveforms, signal shaping and bit-detection is performed by the receiver implemented in software. The block diagram of the receiver used for bit-detection is given in Figure 4. After digitization of the acquired waveforms, a compensation is carried out to counteract the relative delay between the multiple input signals, which is caused by the slanted orientation of the grating with respect to the tangential direction of the metaspiral. A DC and gain correction and adaptive equalization are performed based on an error signal e_k , which is calculated as the difference between the signal at the input of the bit-detector and a desired signal d_k . After equaliza-



Fig. 3. The 2D optical storage principle.

tion a sample-rate converter (SRC) is present to obtain a bitsynchronous replay signal y_k , at the input of the bit-detector. The bit-detector is a stripe-wise Viterbi detector [4] which is dealt with in the next subsection.



Fig. 4. Block diagram of the software receiver.

In case of the hexagonal format, the noiseless reference signal is calculated by passing the detected bits \hat{a}_k through a circularly symmetric, bi-linear, 1-shell channel model [5], which is given by, for a cluster of 7 closely packed bits:

$$d_k = 1 - c_0 - c_1 \sum_{i=1}^{6} \hat{a}_i - \alpha \sum_{\substack{i=1\\j=1+(i \mod 6)}}^{6} \hat{a}_i \hat{a}_j - \beta \hat{a}_0 \sum_{i=1}^{6} \hat{a}_i.$$
(1)

Here c_0 and c_1 are the linear coefficients of the central bit $\hat{a}_0 \in \{0, 1\}$ and the nearest neighbor bits $\hat{a}_i \in \{0, 1\}$, respectively. In Eq. (1), α is a bi-linear coefficient for the interaction between two neighbor bits, while β is a similar coefficient for interaction between a neighbor bit and the central bit.

3.3. Stripe-Wise Bit-Detector

The largest hardware complexity in the receiver is associated with the 2D bit-detector. A full-fledged 2D-Viterbi bitdetector is by far impractical because of the enormous statecomplexity of the associated trellis. Instead, the stripe-wise Viterbi bit-detector [4] will be used as a slightly sub-optimal but quite practical bit-detector (see Figure 5).

A stripe consists of a limited number of bit-rows (2 or 3). A set of Viterbi bit-detectors is devised, one for each stripe. The bits outside of a given stripe that are needed for the computation of the branch metrics, are taken from the output of a neighboring stripe, or are assumed to be unknown (in a first iteration). The top-stripe denoted V00 (containing as its top row, the bit-row closest to the top guard band) is processed while using the bits of the guard band as known bits. The output of V00 are the bit-decisions in the 1^{st} bitrow. The stripe V02 contains the 2^{nd} and 3^{rd} bit-rows, and is processed with a delay that matches the back-tracking depth of the Viterbi-detector of V00; in this way, the output of V00 can be used for the branch metrics of V02. This procedure is continued for all stripes in the broad spiral. The processing is performed in a bi-directional way starting from both guard bands towards the middle of the broad spiral. This constitutes one iteration of the stripe-wise detector. Subsequently, this procedure can be iterated where now also the bits determined in a previous iteration can be used as side-information for a stripe. The iterative detection performance converges fastly, and can be stopped after a small number of iterations (typically 2). Further reduction of the state-complexity of the stripe-wise scheme [4] can be realized via local sequence feedback, hereby lowering its silicon implementation costs.



Fig. 5. Two iterations of stripe-wise processing are shown. Each iteration is performed by a "<"-shape of stripe processors that proceed from the guard band to the center of the meta-spiral. The 2^{nd} iteration - which corresponds to the left "<"-shape - uses stripes with 3 bit-rows per stripe, one more than the 2 bit-rows per stripe of the 1^{st} iteration.

4. MASTERING

Two mastering methods are applied to manufacture stampers for the ROM-discs: Liquid Immersion Mastering (LIM) and Electron Beam Recording (EBR).

LIM is an optical mastering technique, that uses a 257 nm deep-UV laser and an immersion lens with NA = 1.2,

which is realized by using a fluid between the lens and the medium [6]. LIM is used for the RLL coded format. EBR [7] uses electrons to write patterns into the resist during the mastering process: it enables writing of the very small pits that are required for the hexagonal format. Figure 6 shows three identical meta-spirals, containing the hexagonal code. Note the track pitch (119.5 nm), the small size of the pits (70 nm) and the small separation between the pits (138 nm).



Fig. 6. SEM picture of an EBR master.

5. EXPERIMENTAL RESULTS

Measurements have been performed on both LIM and EBR discs. The LIM discs contained a d=1 RLL code, with a CBL of 66.7 nm and a track pitch of 220 nm (38 GB) and 200 nm (41 GB) respectively. The EBR discs contained the hexagonal format with a bit-to-bit distance of 165 nm (35 GB) and 138 nm (50 GB). Using conventional BDlike error correction schemes, the (channel) bit Error Rate (bER) upon read-out has to be lower than 3e-4. The lowest achieved bER values are given in Table 1. Apart from nominal performance, the system should also perform well at sub-optimal conditions. Therefore, measurements at various disc-tilt values have been carried out. For the 50 GB EBR disc, the disc tilt margins in both tangential and radial direction are shown in Figure 7. It is clear that large margins can still be maintained, indicating the feasibility of even higher capacities.

LIM	bER	EBR	bER
38 GByte	8e-5	35 GByte	1e-6
41 GByte	7e-5	50 GByte	2e-5

Table 1. Channel bit Error Rate (bER) for discs masteredby LIM and EBR.

The signal level of a detected bit is highly dependent on its neighboring bits, due to the severe 2D inter-symbol interference (ISI). By plotting the different levels for all possible bit-configurations within 1 shell of the hexagonal lattice, a signal level plot is obtained, showing the individual levels and total modulation or signal range. From the level plot of Figure 8, it is clear that the modulation can be improved i.e.



Fig. 7. Channel bit-Error Rate as function of radial and tangential tilt for EBR disc with hexagonal format at 50 GB.

it is not 'full-range', but rather 'half-range'. This is due to the fact that the disc has not yet been optimized for the optimal pit diameter. Therefore, an increase in signal-to-noise ratio is still to be expected, again meaning that an additional capacity increase is feasible.



Fig. 8. Signal levels for the different clusters.

During disc read-out several read-out speeds have been used. The highest achieved data-rate for the hexagonal format, at which the bER was still within the specifications, was 560 Mbit/sec. Currently these values are limited by the anti-aliasing filters used in the electronics.

A simple theoretical analysis of error patterns in case of the 2D hexagonal format was already given before [8]. Here a linear channel is assumed and an exhaustive search is done for data patterns that have a minimum Euclidian distance. The worst case error patterns are sequences of alternating '+1' and '-1' symbols, which are referred to as Nyquist sequences. From the 50 GB experiments, it is confirmed that the predicted Nyquist error sequences are indeed responsible for a large fraction of the errors that occurred during read-out, especially for increasing values of disc tilt.

6. CONCLUSIONS

By applying advanced signal processing and using 2D data formats to store data on an optical disc, it is possible to obtain a capacity increase of at least a factor of 2, without the need of changing the read-out physics. Single-layered discs with capacities up to 50 GB have been manufactured and read out successfully, using standard Blu-ray Disc optics. From measured tilt margins and modulation plots it is clear that even higher capacities are feasible. Moreover, by the parallel read-out of the 2D format, a large increase in user data-rate is obtained (up to 560 Mbit/sec), providing a feasible solution to the data-rate bottleneck.

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