相変化型光ディスクへの多値記録技術

Multi-level Recording on Phase-change Optical Discs

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要　　旨

短波長化と高NA（ Numerical Aperture：開口数）技術の導入により，CD-R/RWから書き換え型DVDへと光ディスクの大容量化が進む一方，多値記録による高密度，高転送レートの実現が注目されており，特に多値記録は，光ディスク装置の光学系を変更せずに容量を増加できるので，容易に商品の付加価値を高められる利点がある．相変化型光ディスクであるDVD+RWディスクを用いて，多値データの値によって記録マーク長を変化させる面積変調により，8値記録を実現した．信号再生時の符号間干渉を隣接データとの相関と見なし，パタン認識技術によって多値データを判定する多値判定方式 Data Detection using Pattern Recognition（DDPR)及び，8値データ（3ビット）の最下位ビットに制限を加えたデータ変調方式 LSB (Least Significant Bit) Limited Modulation (LLM)を新規に開発し，両者の組合せにより，DVDの1.7倍容量を達成した．

ABSTRACT

The capacity of optical discs has been increased by using laser diodes with shortened wavelength and lenses with a larger numerical aperture. This has enabled, for example, the development of rewritable DVDs with greater disc capacity than CD-R/RWs. Recently, however, an optical disc system using multi-level recording has been recognized as a more effective means of achieving higher data capacity and transfer rates. Because this system requires no changes to the pick-up head in the disc drive, it makes it easy to increase the values of the disc system. Following up on this, in this paper the multi-level recording on a rewitable DVD is reported. The eight-level data are recorded on a DVD+RW disc, i.e., a phase-change rewritable optical disc, using area modulation where the length of the recording mark on the disc varies with the level of data. The newly-developed technologies that make this possible are Data Detection using Pattern Recognition (DDPR) and LSB (Least Significant Bit) Limited Modulation (LLM). DDPR detects multi-level data by regarding inter-symbol interference as the correlation between adjacent data. LLM modulates binary data into eight-level (three-bit) data where the LSB is bound by certain rules. Coupling these technologies makes it possible to achieve a DVD with capacity 1.7 times that of a conventional DVD.

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1. INTRODUCTION

A rewritable phase change optical disc that is compatible with the DVD-ROM was released as the next generation of CD-RW. The data capacity of this rewritable DVD disc is 4.7G bytes and that is about seven times that of a CD-RW. The data transfer rate is about 88 Mbps for reading and about 26 Mbps for writing. However, greater data capacity is needed to cope with the increased amount of information that has been accumulated over the last few years. And a higher data transfer rate will also be needed to keep pace with the speedups of computer systems. The current aim of optical disc development is to increase both data capacity and the data transfer rate. One of the solutions to this task is focused to use multi-level recording without any changes being made to the optical pick up head. [1]

We have developed two original methods for multi-level data recording on optical discs. One is a data detection method named Data Detection using Pattern Recognition (DDPR) [2] in order to enlarge the recording margin and the playback margin that are the parameter defined for recording quality. The other is a new data modulation process, LSB (Least Significant Bit) Limited Modulation (LLM), in corporation with DDPR in order to reduce data errors. In this paper we have explained DDPR and LLM, in addition to the experimental results that the coupling LLM with DDPR was effective in reducing data errors using DVD+RW disc system.

2. MULTI-LEVEL RECORDING

2-1 Comparison of recording and playback methods

Fig.1 and Fig.2 show the comparison between the conventional method and multi-level recording method. In the conventional method, information is recorded and reproduced as the time interval data. The data is equivalent to the mark length or the space length. On the other hand, in the multi-level recording, information is recorded and reproduced as the signal amplitude. The data is equivalent to the rate of mark size occupying in a data cell.

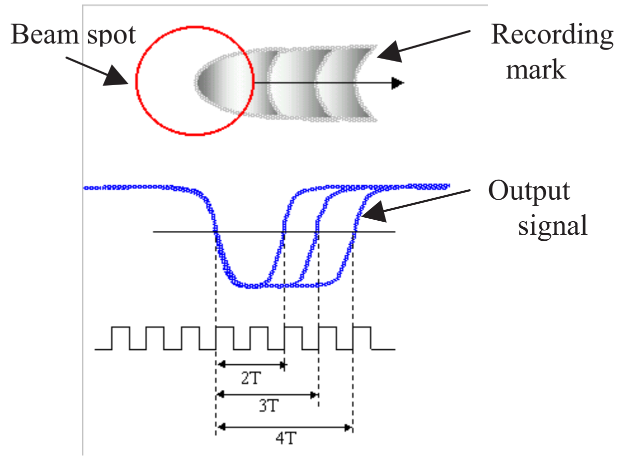


Fig.1 The conventional method, the relationship between mark and output signal in bi-level recording.

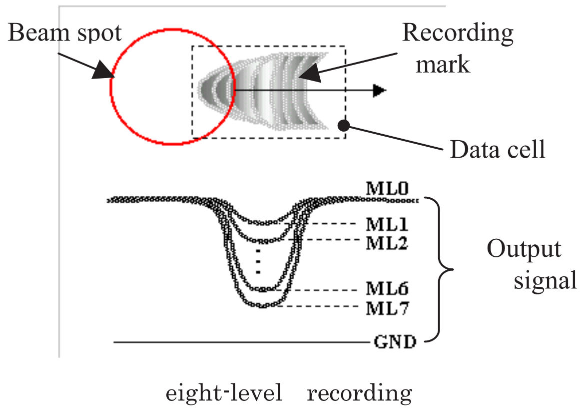


Fig.2 The multi-level recording method, the relationship between mark and output signal for eight-level recording.

2-2 Sigma to Dynamic Range

An evaluation of data recording quality involves the time variations of playback signal's edges (jitter) in the conventional case of bi-level recording. In the case of multi-level recording, Sigma to Dynamic Range (SDR) has been proposed for the evaluation of recording quality. Fig.3 shows the definition of SDR. "SDR is the ratio of the standard deviation of a recorded level to the total dynamic range between minimum and maximum reflectivity." Usually the bit error rate (BER) needs to be about 10^{-5} before the performance of the error correction that is generally used for optical discs. The SDR needs to be less than 2.0% for data detection using a fixed threshold level to achieve a BER of 10^{-5}. [3] To attain stability in the tolerance of compatibility and mass production, it is preferable to enlarge the SDR margin.

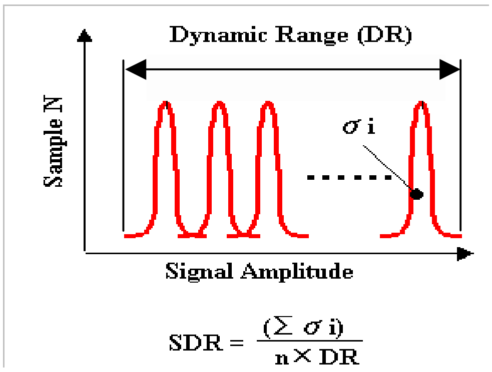


Fig.3 SDR has been proposed for the evaluation of recording quality. SDR is calculated as a ratio of the averaged value of σ in all levels to DR.

2-3 Multi-level Recording Marks

Fig.4 shows the TEM image of multi-level recording marks on the phase-change disc of DVD+RW. The width of a data cell is 0.74 μm and its length is 0.4 μm. Under this geometry condition the maximum mark of multi-level recording is equivalent to the minimum mark of DVD, and the recording density becomes double of DVD's. It needs to control the write pulse signal in order to record these small marks accurately.

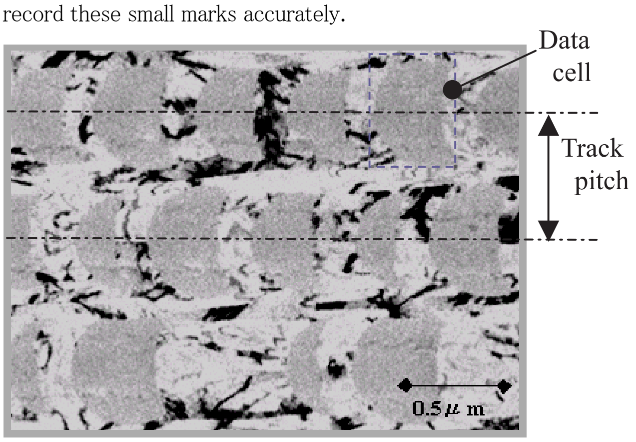


Fig.4 TEM image of multi-level recording marks, cell size is 0.74μm ×0.40μm, Track pitch is 0.74μm, mark length is 0 to 0.36μm.

3. DDPR

3-1 Principle of DDPR

Multi-level data is recorded as a mark of variable length in a data cell on a spiral track of a disc. The length of the mark was controlled so that the reflectivity from the mark would have eight different levels. The higher the recording density becomes, the smaller the data cell becomes in comparison with the diameter of beam spot, as shown in Fig.5. Inter-symbol interference (ISI) occurs and varies the amplitude of the playback signal in the center of data cell.

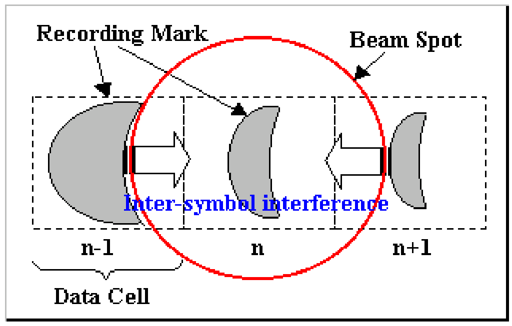


Fig.5 Explanation of the inter-symbol interference (ISI). Premark position is n-1, postmark position is n+1. There are three data cells in a beam spot.

Fig.6 shows an example of amplitude variations caused by ISI. Playback signal waveforms corresponding to three continuous multi-level data (n-1, n, n+1) are shown. T(i, j, k) represents the amplitude of multi-level data(n), whose level is j , between predata(n-1), whose level is i, and postdata(n+1), whose level is k. Though T(0,1,0) and T(7,0,0) are very close to each other, they must be detected as different levels(1 and 0). It is difficult to distinguish between them for data detection using a fixed threshold level.

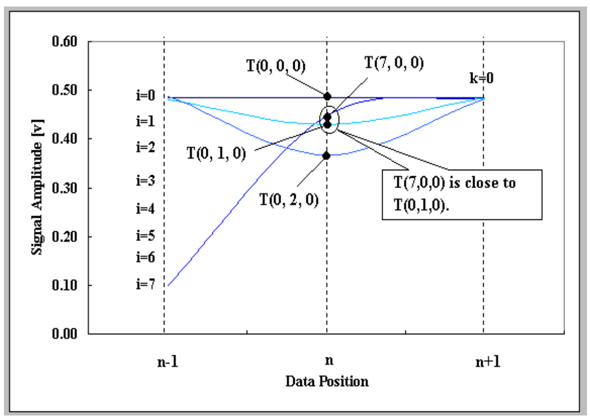


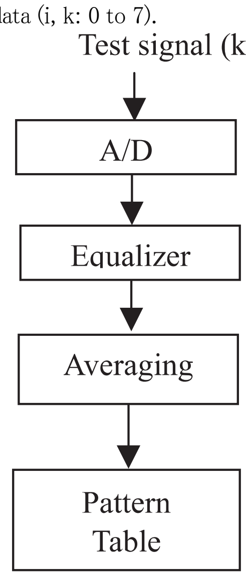
Fig.6 Example of ambiguous waveforms. Premark position is n-1 and postmark position is n+1. The signal value of T(7, 0, 0) is close to that of T(0, 1, 0).

The ISI still remains after equalization using a linear Finite Impulse Response (FIR) filter. This ISI is caused by pre and post data and its effect seems to be nonlinear. The effect of ISI becomes larger when the number of data levels is increased and the dynamic ranges of each level are narrowed. Therefore, we developed DDPR that detects multi-level data using a correlation obtained from three continuous data.

3-2 Signal Process of DDPR

DDPR is composed of two steps. One is the process of "making pattern table" which learn the ISI and the variation of signal amplitude. The other is the process of "data detection using the pattern table".

Fig.7 shows the signal processing flow for making a pattern table before using data detection. The test signal read from the disc is converted into a digital signal using an A/D converter. The digital signal is equalized to remove inter-symbol inference using a five-tap equalizer. The output signal of the equalizer is averaged using the same known data. The averaged value is stored into the table. T(i, j, k) presents the averaged value of the equalized signal, corresponding to the center data (j:0 to 7) between pre and post data (i, k: 0 to 7).



Pattern table

No	I	j	k	Signal
1	0	0	0	T(0, 0, 0)
2	0	1	0	T(0, 1, 0)
3	0	2	0	T(0, 2, 0)
4	0	3	0	T(0, 3, 0)
5	0	4	0	T(0, 4, 0)
6	0	5	0	T(0, 5, 0)
7	0	6	0	T(0, 6, 0)
8	0	7	0	T(0, 7, 0)
9	1	0	0	T(1, 0, 0)
:	:	:	:	:
511	7	6	7	T(7, 6, 7)
512	7	7	7	T(7, 7, 7)

Fig.7 Making pattern table. T(i, j, k) presents the averaged value of the equalized signal corresponding to the center data (j:0 to 7) between pre and postdata (i, k: 0 to 7).

Fig.8 shows the signal processing flow of the data detection using the pattern table generated above. The data signal is converted into a digital signal and equalized using the same flow found in Fig.7. The equalized signal is pre-detected using fixed threshold levels.

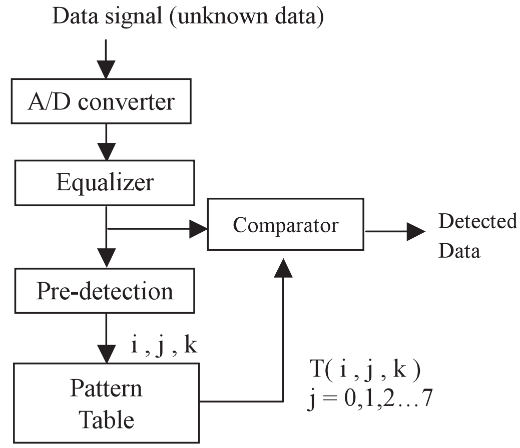


Fig.8 Data detection using the pattern table. The comparator outputs a candidate that has minimum error as a detected data.

Fig.9 shows the amplitude histograms of eight-level data after equalizing the test signal. The threshold levels are set between the distributions of each level. Pre-detection fixes the levels (i and k) of pre and postdata using the threshold levels. After the pre-detection, eight candidates (T(i, j, k): j is 0 to 7.) are picked up from the pattern table. The errors between the equalized signal and the candidates are calculated. The comparator outputs a candidate that has minimum error as a detected signal. This pattern recognition process was based on ISI from pre/post marks after the equalization.

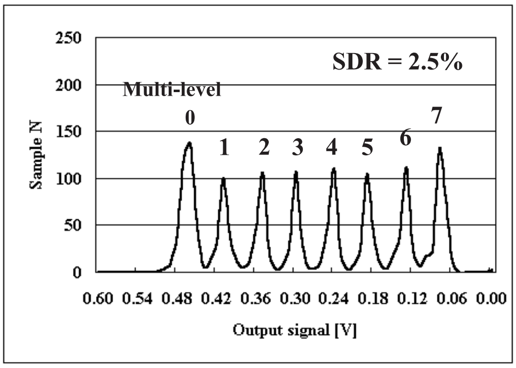


Fig.9 The amplitude histograms of eight-level data after equalizing. Cell length is 0.40 μm. SDR is 2.5%.

3-3 Experiment and Results of DDPR

Multi-level data was recorded on a DVD+RW disc of track pitch 0.74 μm at linear velocities, ranging from 3.5 to 7.0 m/s using a DVD+RW drive. A laser diode of 650nm wavelength and an objective lens of 0.65-NA (Numerical Aperture) are mounted on its pick-up head. The effect of the DDPR on BER and SDR for various data-cell lengths was investigated. For example, in Fig.9, the averaged SDR was 2.5%, where the data-cell length was about 0.40 μm and the data capacity was twice that of the DVD. Fig.10 shows that using DDPR reduces BER more effectively than such data detection using fixed threshold levels as pre-detection on the BER vs. SDR plane. The BER of the order of 10^{-5} was achieved using DDPR for SDR ≦2.7%. DDPR enlarged a SDR margin from 2.0 to 2.7%. DDPR using code modulation should improve BER and should be able to design for a feasible multi-level recording system.

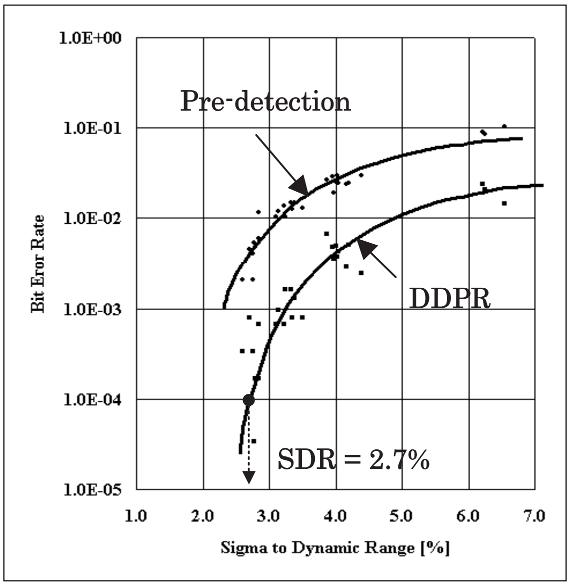


Fig.10 Comparison between DDPR and Pre-detection, DDPR enlarged SDR margin from 2.0% to 2.7%.

4. LLM

4-1 Principle of LLM

Fig.11 shows the example of detected level deviation after DDPR process. We confirmed that the level error is within ±1 from this result. This deviation of ±1 level causes the bit reverse of LSB. Therefor it's possible to correct the level error by restricting LSB of multi-level data.

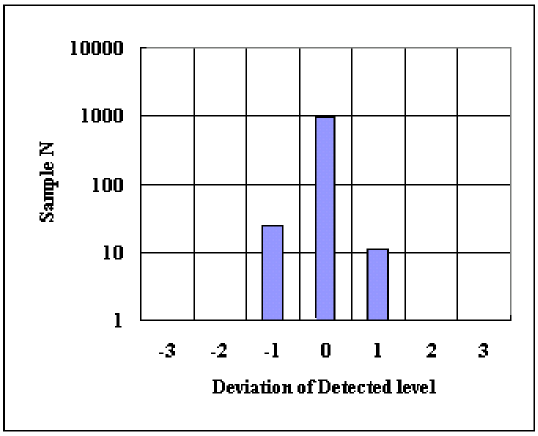


Fig.11 Example of level deviation histogram after DDPR process, the level error is ±1.

4-2 Modulation using LLM

Fig.12 shows data arrangements before and after LLM. The 11-bit input data (D0, D1, … D10) are converted into a set of four symbols (S0, S1, S2, S3). As a symbol is eight-level data, it contains three bits. The LSBs (L0, L1, L2, L3) of the symbols are generated from three bits (D0, D1, D2) in the input data using a conversion table. The rest of the input data (eight bits: D3, D4, … D10) are arranged directly into the MSB (Most Significant Bit) side of the symbols sets as shown in Fig.12.

Fig.13 shows the conversion table used in LLM. The three bits (D0, D1, D2) are converted into four bits (L0, L1, L2, L3). This table has two conversion rules that are selected by a parameter “P” (0 or 1) defined in every set. P (n) in the n-th set is defined as the result of exclusive-or operation between P (n-1) and L3 (n-1) in the previous (n-1)-th set. The initial value of P (1) is 0. The four-bit converted data pattern in the table differs from adjacent patterns where two or more bits are different from each other. For example, (D0, D1, D2) = (0, 0, 0), (0, 0, 1), and (0, 1, 0) are converted into (L0, L1, L2, L3) = (1, 1, 1, 1), (1, 1, 0, 0), and (1, 0, 1, 0), respectively and where P = 0. Comparing (1, 1, 1, 1) with (1, 1, 0, 0) and (1, 1, 0, 0) with (1, 0, 1, 0), there are two different bits in each pattern. One redundant bit enlarges the code distance (Hamming distance). Moreover, P generates a correlation between sets. This correlation is also useful in the demodulation process similar to maximum likelihood decoding.

4-3 Demodulation using LLM

Fig.14 shows the signal processing flow of LSB Limited demodulation. An input multi-level signal is detected to generate two candidates for a symbol by using threshold levels. Because the conversion table limits the LSB of a symbol, a symbol candidate should be an even or odd level. The nearest two (even and odd) levels are chosen as candidates from eight levels. Using two

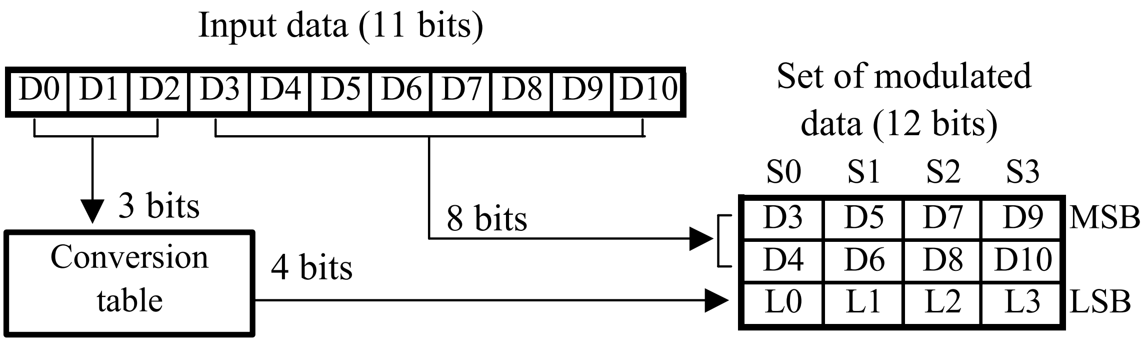


Fig.12 Data arrangements before and after LLM, the 11-bit input data (D0, D1, … D10) are converted into a set of four symbols (S0, S1, S2, S3). The LSBs (L0, L1, L2, L3) of the symbols are generated from three bits (D0, D1, D2).

Input			P = 0				P = 1			
D0	D1	D2	L0	L1	L2	L3	L0	L1	L2	L3
0	0	0	1	1	1	1	1	1	1	0
0	0	1	1	1	0	0	1	1	0	1
0	1	0	1	0	1	0	1	0	1	1
0	1	1	1	0	0	1	1	0	0	0
1	0	0	0	1	1	0	0	1	1	1
1	0	1	0	1	0	1	0	1	0	0
1	1	0	0	0	1	1	0	0	1	0
1	1	1	0	0	0	0	0	0	0	1

P: Parameter in every set to select conversion rules on the table

P (n) = P (n-1) xor L3 (n-1)

P (1) = 0

n: set number

xor: exclusive-or operation

Fig.13 The conversion table used in LLM. The three bits (D0, D1, D2) are converted into four bits (L0, L1, L2, L3). This table has two conversion rules that are selected by a parameter "P" (0 or 1) defined in every set.

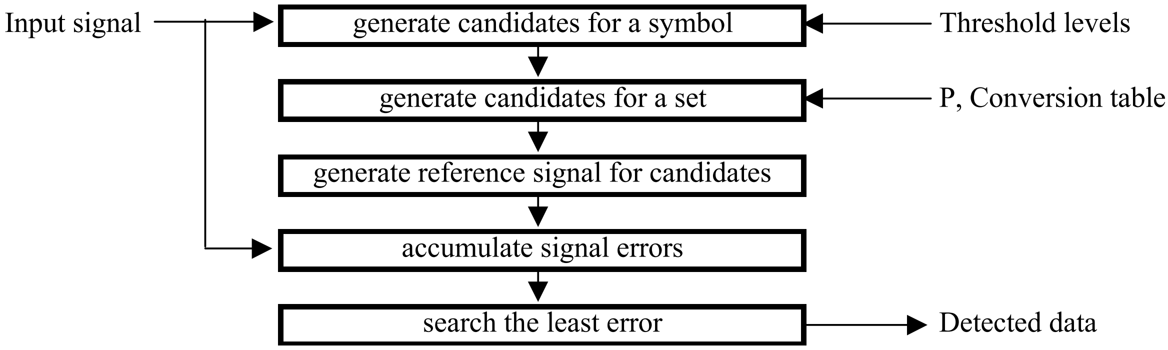


Fig.14 The signal processing flow of LSB Limited demodulation.

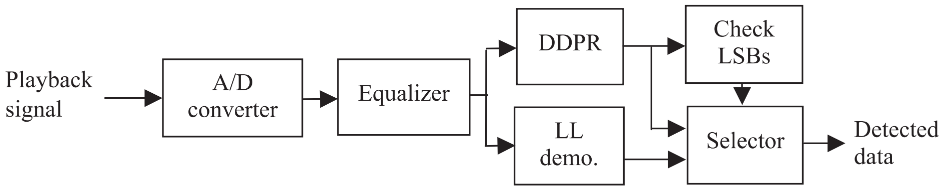


Fig.15 Signal Process of data detection coupling LLM with DDPR

candidates for a symbol, eight candidates for foursymbols in a set are generated according to the parameter P in the set and the conversion table. A reference signal value corresponding to a candidate for a symbol is generated. A signal error (difference) between the input signal and the reference signal value for each symbol is accumulated in several sets. The candidate with the least error is output as detected data.

4-4 Coupling LLM with DDPR

Fig.15 shows the signal processing flow of data detection coupling LLM with DDPR. The playback signal read from an optical disc is converted into a digital signal using an A/D converter. The digital signal is equalized to remove inter-symbol interference using a 7-tap equalizer. After equalization DDPR and LL demodulation are processed in parallel. The LSBs of output data in a set from DDPR are checked as to whether they obey the conversion rule of the table used in LLM. When they match the rule, the result of DDPR is output a detected data through a selector. If they do not match, the result of LL demodulation is output as detected data. The DDPR detects multi-level data using the correlation between pre- and post data. The LSBs in a set can be used as error detection code. The LL demodulation detects multi-level data according to the conversion rule in LLM and the correlation between sets generated by P. If P is incorrect, symbol errors may propagate in several sets. The DDPR is able to terminate the error's propagation. Thus, the DDPR and LLM compensate for each other's faults

4-5 Experiment and Results of LLM + DDPR

Fig.16 is a block diagram of the experimental system. Random data was generated and LL modulated into multi-level data using a personal computer. A write-pulse generator converted the multi-level data into a driving signal for a laser diode in an optical pick-up head (PU). Multi-level data was recorded on a DVD+RW disc the same DVD+RW drive as mentioned in 3-3. The playback signal was converted into a digital signal using an A/D converter with a clock synchronized with the playback signal using a PLL (Phase-Locked Loop) circuit. The data detection shown in Fig.15 was processed using software on the personal computer.

Fig.17 shows an example of playback signal and clock signal waveforms. Using DDPR and LLM together achieved a BER (Bit Error Rate) of the order of 10^{-5} before error correction where recording density was 1.7 times that of a conventional DVD, assuming that a format efficiency of ECC (Error Correction Code) was the same as that of a standard DVD. The BER was 10^{-4} where recording density was twice as great. Using only DDPR, the recording density was 1.4 times where the BER was 10^{-5}..

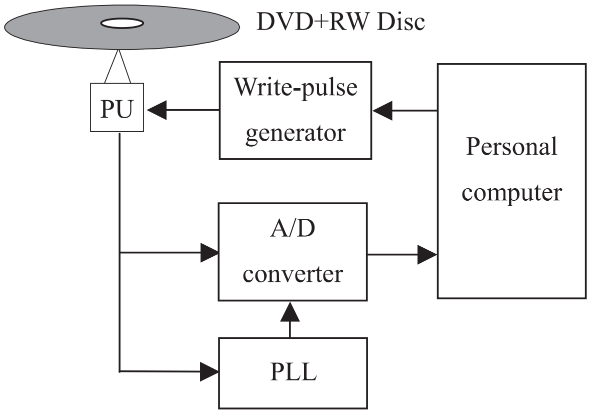


Fig.16 The block diagram of the experimental system.

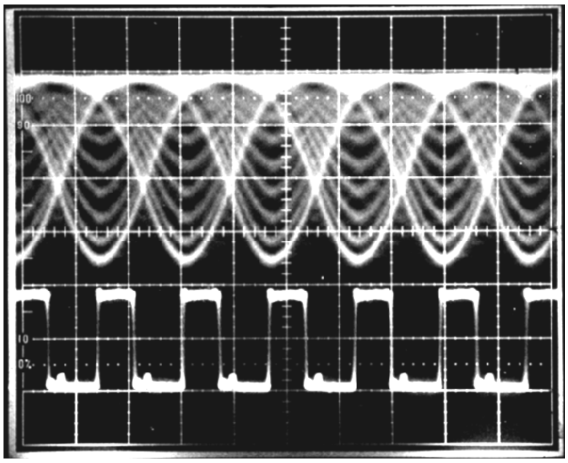


Fig.17 Example of playback signal and clock signal waves.

5. CONCLUSIONS

We developed the new method of the coupling LLM with DDPR for the multilevel recording. Our experiments confirmed that coupling LLM with DDPR was effective in reducing data errors and increasing recording density. This effective performance enabled to make 1.7 times recording density of a conventional DVD. We intend to refine this method and apply it to a blue-laser optical disc system.

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