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RESEARCH ARTICLE

# Optimized multi-dimensional optical storage reading strategy

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**Abstract** A novel multi-dimensional (MD) optical storage was presented, which was realized by utilizing the space between tracks. Based on scalar diffraction theory, the channel bits parameters of the multi-dimensional optical storage were optimized, and the linear and nonlinear signals were analyzed accurately. Therefore, the format of the multi-dimensional optical disc was obtained, which makes the detection of readout signal easier. With respect to servo, coding and readout physics parameter of channel, the multi-dimensional optical disc is compatible with traditional disc such as Blu-ray disc (BD). Also, the novel multi-dimensional optical storage is able to achieve a doubled density and a ten-fold readout data rate compared with traditional optical discs.

**Keywords** multi-dimensional (MD), optical storage, scalar diffraction model, partial response

## 1 Introduction

Multi-level (ML) technology can increase the storage capacity without changing the readout optics and mechanism [1,2]. Multi-dimensional (MD) optical storage also can reach the aim. In the present optical disc storage, user data is recorded along a single spiral track with one dimensional run-length-limited (RLL) codes. The laser light from the optical unit of disc is shot at the bottom of optical disc, and is diffracted by the pits and lands on a single track. The focused spot of the laser light is circumferential symmetry, and the track of the optical disc is single dimension. Therefore, only part of the focused spot covers the single track, and the other part of the focused spot covers the section between tracks. The energy of the laser light is not utilized effectively.

MD optical storage can solve this problem, meanwhile increase the data density. In this paper, a novel MD optical storage is presented. Based on the traditional optical disc, not only can the track be used to record user data in one dimension, but the space between two tracks is also utilized as the other dimensional recording. The space between two tracks is called sub-track, and the traditional track is still called track. The modulation method of user data recorded in the tracks, RLL modulation is also used in the sub-tracks. As same as the tracks, the sub-tracks also record user data by using recording marks. The recording method of the tracks is different from the sub-tracks. The MD optical storage can increase the density of the optical disc, and meanwhile is compatible with the traditional discs.

A project called Two-Dimensional Optical Storage (TwoDOS) has been developed, in which the information on the disc fundamentally has a two-dimensional (2D) character [3,4]. The format of the 2D disc is based on a broad spiral, which consists of a number of parallel bit-rows that are aligned with each other in the radial direction in such a way that a 2D close-packed hexagonal lattice of bits results. Though this kind of 2D disc can utilize the area of the focused spot because of the hexagonal lattice of bits, it cannot be compatible with the traditional one-single-track disc. Therefore, we propose the MD optical storage which is realized in two kinds of formats. The first format is based on a couple of tracks, which consist of the spiral track and its accompanying sub-track. On a traditional optical disc, the track is a spiral from the inside to the outside of the disc. In the first format, an accompanying sub-track is inserted into the space between the inner track and outer track. Using the traditional optical readout system, the user data recorded on the MD optical disc can be obtained. The second format is based on a broad spiral, which consists of a number of parallel tracks and sub-tracks.

## 2 Basic principle

Based on the traditional optical disc, not only can the track be used to record user data in one dimension, but the space

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between two tracks is also utilized as the other dimensional recording. The space between two tracks is called sub-track. As that in the traditional tracks, the modulation method of the data in the sub-tracks is RLL modulation. The only difference between the tracks and the sub-tracks is the recording marks. The recording method of the tracks is non return to zero-invented (NRZI), while the recording method of the sub-tracks is non return to zero (NRZ).The recording marks in the traditional tracks are some RLL continuous pits, while the recording marks in the sub-tracks are a number of single round pits, and every single round pit only occupies one channel bit length. In the track, the pit represents “1” and the land represents “0”, while in the sub-track, the pit represents once flipping, from “1” to “0” or from “0” to “1”, and the land represents being the same bit with the last channel bit.

The MD optical storage is realized in two kinds of formats. Figure 1(a) shows the schematic format for the first format of the MD optical storage, and Fig. 1(b) shows the schematic format for the second format of the MD optical storage.

The first format is based on a couple of tracks, which consist of the spiral track and its accompanying sub-track. On a traditional optical disc, the track is a spiral from inside to outside of the disc. In the first format, an accompanying sub-track is inserted into the space between the inner track

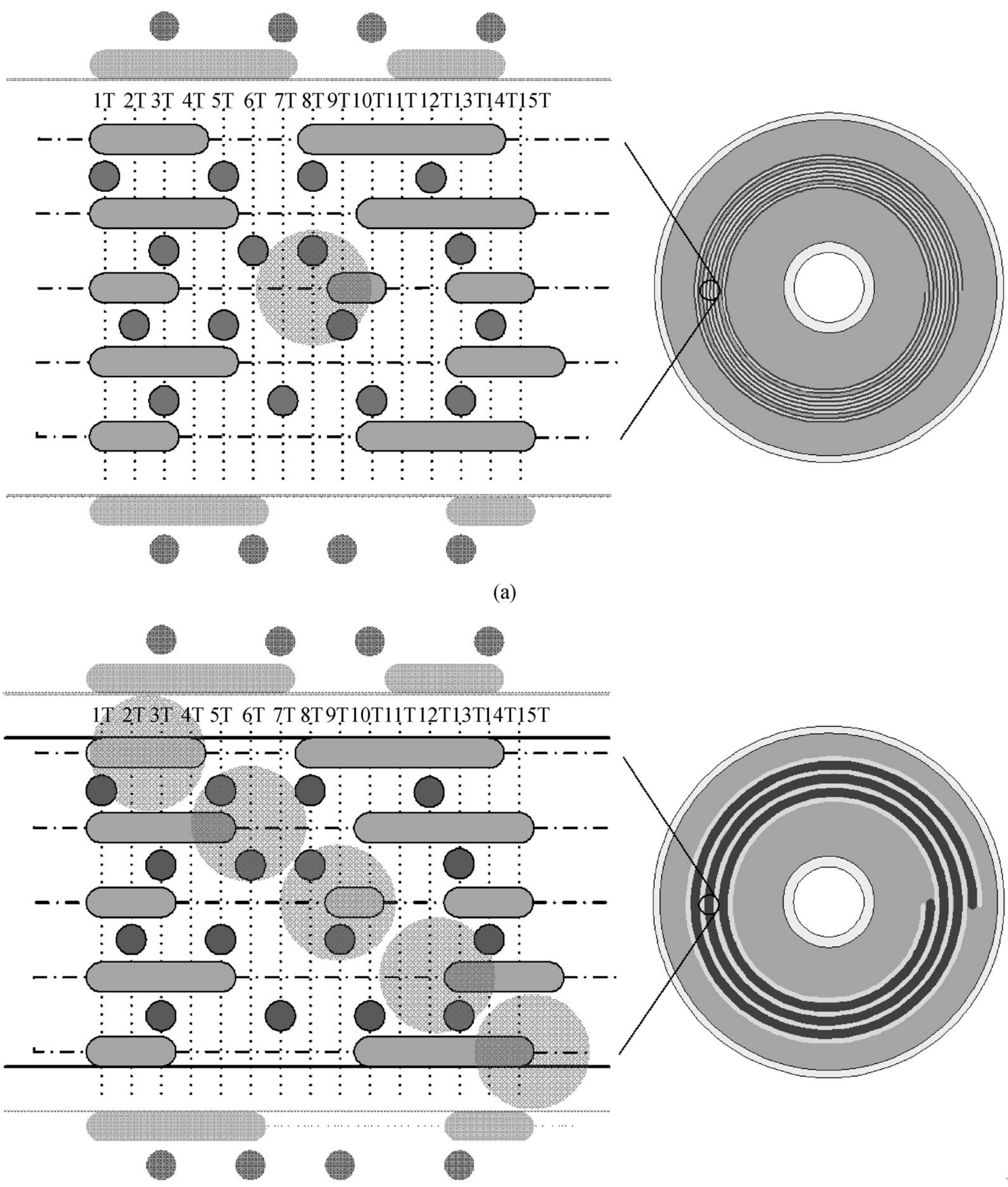


**Fig. 1** Schematic format of multi-dimensional (MD) optical storage. (a) Schematic format for the first format of the MD optical storage; (b) schematic format for the second format of the MD optical storage

and outer track. Using traditional optical readout system, user data recorded on MD optical disc can be obtained.

The second format of the MD optical storage is based on a broad spiral, in which the user data is recorded in the form of 2D features. The broad spiral consists of a number of traditional tracks, as same as the ones in the common disc, and a number of sub-tracks are inserted between the traditional tracks. Successive revolutions of the broad spiral are separated by a guard band consisting of one empty bit row. A multi-spot light path for parallel readout is utilized.

Because of the similarity with TwoDOS project, the manufacture of MD disc can refer to that of TwoDOS project [5]. For every pit on the sub-track only occupies one channel pit length, very small pits are required. Using an electron-beam recorder (EBR) can obtain enough small pits [6]. In regard to track-to-track data synchronization, by using a single writing spot, two-dimensional structures can be achieved [7].

For the design of the novel MD optical storage formats, accurate analysis of the optical channel is important.

## 3 Optical channel analysis

### 3.1 Scalar diffraction model

Vector diffraction theory is rigorous, but would be impractical because of computational complexity [8,9]. A more convenient yet still sufficiently accurate way of simulation is accomplished with a model based on scalar diffraction theory as introduced by Hophins [10]. Based on the scalar diffraction theory by Hophins, a nonlinear signal-processing model has been presented by Coene [11].

According to the scalar diffraction theory by Hophins and the nonlinear model by Coene, the power of the optical wave front in the exit pupil, which is integrated within the so-called central aperture (CA) used for the physical detection, yields the value of the detected signal waveform, which is denoted $I_{\text{sum}}(R_p)$, for which one has

$$I_{\text{sum}}(R_p) = \int_{(\text{CA})} \left|\text{FT}_{R\to\omega}[p(R-R_p)r(R)]\right|^2 \text{d}\omega, \quad (1)$$

where $\omega$ represents the 2D spatial frequency vector in the exit pupil plane, $R$ represents the 2D position vector in the disc plane, $\text{FT}_{R\to\omega}$ represents a 2D Fourier transform from the disc plane toward to the exit pupil plane, $p(R-R_p)$ represents the complex-valued probe function of the focused laser spot centered on position $R_p$, and $r(R)$ represents the complex-valued reflection function of disc information layer.

The complex-valued reflection function of the disc information layer is written in the following notation:

$$r(R) = 1 + \sum_j u_j(\text{e}^{\text{i}\varphi}-1)W(R-R_j). \quad (2)$$

In Eq. (2), $u_j$ denotes bit value (0,1), $\text{e}^{\text{i}\varphi}$ is the reflection function at pit area, where $\phi$ is the double-pass phase depth, and $W(R-R_j)$ is the pit window function centered at position $R_j$, which equal 1 inside pit area and equal 0 outside pit area.

In order to notational convenience, the so called bracket notation is introduced for the complex-valued optical wave front in the exit pupil [12]. The complex-valued optical wave function in the exit pupil is represented as

$$|\psi\rangle = \text{FT}_{R\to\omega}[p(R-R_p)r(R)]. \quad (3)$$

The integral within the CA used for detection is represented by the quantum-mechanical notation as

$$\langle\Phi|\varphi\rangle = \int_{\text{CA}} \Phi^*(\omega)\varphi(\omega)\text{d}\omega. \quad (4)$$

Therefore, according to Hophins's scalar diffraction model, the value of the detected signal waveform is represented simply as

$$I_{\text{sum}} = \langle\psi|\psi\rangle. \quad (5)$$

Combining Eqs. (2) and (3) yields,

$$|\psi\rangle = |\psi_\text{L}\rangle + \sum_j u_j(\text{e}^{\text{i}\varphi}-1)|\psi_j\rangle. \quad (6)$$

In Eq. (6), $|\psi_\text{L}\rangle$ represents the reflection of the focused spot by the land only, and $|\psi_j\rangle$ represents the reflection of the focused spot by the pit area at position $R_j$.

$$|\psi_\text{L}\rangle = \text{FT}_{R\to\omega}[p(R-R_p)], \quad (7)$$

$$|\psi_j\rangle = \text{FT}_{R\to\omega}[p(R-R_p)W(R-R_j)]. \quad (8)$$

Combining Eqs. (5) and (6), we can obtain the value of the detected signal waveform

$$\begin{aligned} I_{\text{sum}} = {} & \langle\psi_\text{L}|\psi_\text{L}\rangle + (\text{e}^{\text{i}\varphi}-1)\sum_j u_j\langle\psi_\text{L}|\psi_j\rangle \\ & + (\text{e}^{-\text{i}\varphi}-1)\sum_j u_j\langle\psi_j|\psi_\text{L}\rangle \\ & + |\text{e}^{\text{i}\varphi}-1|^2\sum_{j,k} u_j u_k\langle\psi_j|\psi_k\rangle. \end{aligned} \quad (9)$$

In Eq. (9), the first term is a constant term, which represents the reflection at the all-land area; the second and third linear terms represent interference between the all-land wave front $|\psi_\text{L}\rangle$ and pit wave front $|\psi_j\rangle$; the last nonlinear term represents interference between two pit wave front $|\psi_j\rangle$.

Further simplifying Eq. (9), we can obtain

$$I_{\text{sum}} = 1 - \sum_j c_j u_j + \sum_{j \neq k} d_j u_j u_k, \tag{10}$$

$$c_j = 2(1-\cos\varphi)(\langle \psi_L | \psi_j \rangle - \langle \psi_j | \psi_j \rangle), \tag{11}$$

$$d_j = e_{j,k} = 2(1-\cos\varphi)\mathrm{Re}(\langle \psi_j | \psi_k \rangle). \tag{12}$$

### 3.2 Channel bits parameter optimization

According to the scalar diffraction theory and nonlinear signal-processing model above, the channel bits parameter can be optimized.

In the readout channel of the MD optical disc, in order to decrease the inter-symbol interference (ISI), we use the partial response maximum likelihood (PRML) to detect the high frequency (HF) signal waveform. Therefore, choosing the proper partial response (PR) coefficient is important.

In order to utilize the focused laser spot more efficiently, the chosen PR channel bits would be approximate to a round. Figure 2 shows the relative position between the channel bits of the track and sub-track, and the PR channel bits is more approximate when the channel bit of the sub-track is 0.5 channel bit behind the channel bit of the track.

Figure 3 shows the channel bits parameter of the track and sub-track. The width of the track and sub-track is equal, denoted by *chw*. The length of the channel bit of the track and sub-track is equal, denoted by *chl*. *pw* represents the width of the pit area in the track. The recording mark of the sub-track is round, of which the diameter is denoted by *da*.

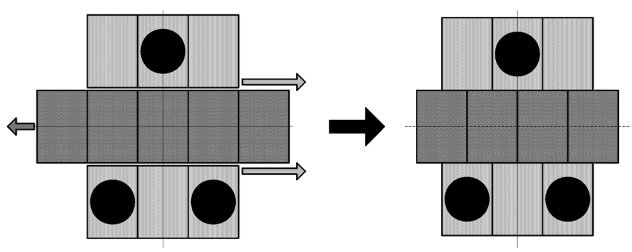

**Fig. 2** Channel bit of the sub-track is 0.5 channel bit behind the channel bit of the track

The MD optical disc is compatible with the traditional disc. In the following discussion, take the Blu-ray disc (BD) as an example. The focused spot and modulation of the MD optical storage has BD characteristics, $\lambda = 405$ nm, numerical aperture (NA) = 0.85 and RLL(1,7).

For the BD disc, the length of the channel bit is 75 nm and the distance between the tracks is 320 nm. Because of the sub-track, the ratio of the track signal to the full signal is decreased. Therefore, in order to increase the signal noise rate (SNR), the length of the channel bit would be increased. Meanwhile, due to the distance between the tracks is enough large, it is decreased to enlarge the capacity.

In Fig. 4, the coefficient $c_j$ of the track is simulated under different length of the channel bit. The laser spot is centered at bit position $j = 0$. According to the coefficient $c_j$, the proper PR channel bits of the track can be obtained. Obviously, the coefficient $c_j$ of four bits nearby the center of the focused spot is larger than other bits. Meanwhile, when $chl$ = 90 nm, the coefficient $c_j$ of $k = \pm 3$ bits is smaller than the center bits by an order of magnitude. Therefore, we choose the *chl* equal 90 nm.

As Fig. 5 shown, when $chl$ = 90 nm, the coefficient $c_j$ of the track is constant. The laser spot is centered at bit position $j = 0$. With the change of the *chw*, the coefficient $c_j$ of the sub-track is also changing. Obviously, the coefficient $c_j$ of three bits nearby the center of the focused spot is larger than other bits. Meanwhile, when $chw$ = 130 nm, the coefficient $c_j$ of $k = \pm 2$ bits is smaller than the center bits by an order of magnitude. Therefore, we choose the *chw* equal 130 nm.

According to the above discussion, we choose the proper PR channel bits, which compose of four bits in the track and three bits in the sub-track. There are 10 possibilities of

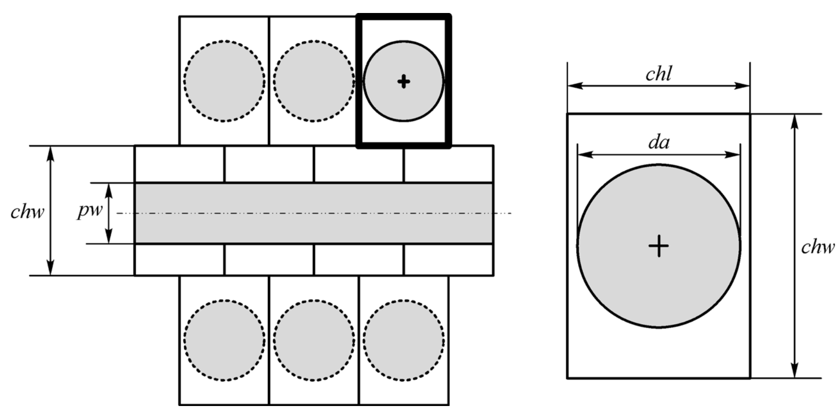


**Fig. 3** Channel bits parameter of the track and sub-track

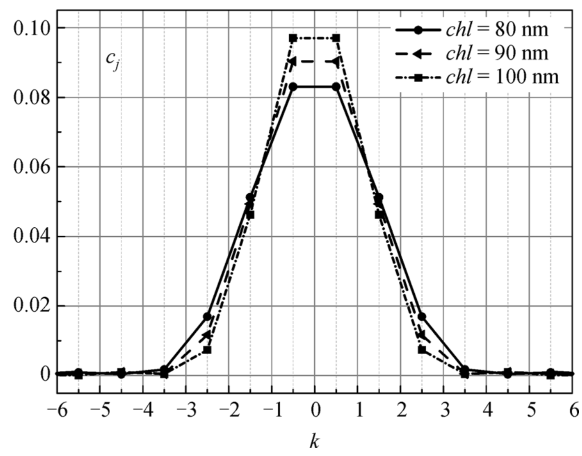


**Fig. 4** Coefficients $c_j$ of the track, when $chl$ = 80/90/100 nm, for BD pick-up unit ($\lambda$ = 405 nm, NA = 0.85)

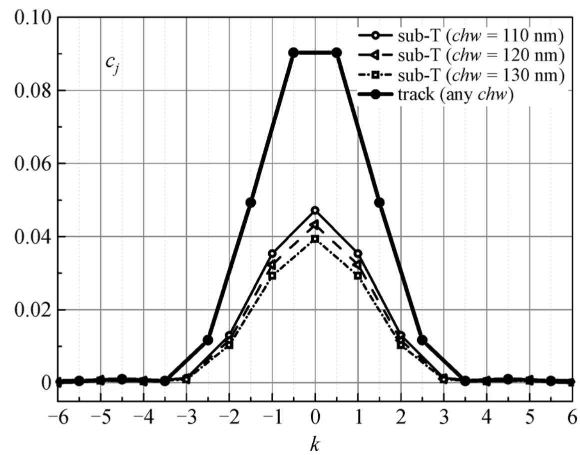


**Fig. 5** Coefficients $c_j$ of the sub-track (sub-T), when $chw$ = 110/120/130 nm, for BD pick-up unit ($\lambda$ = 405 nm, NA = 0.85)

the four PR channel bits of the track, including “0 0 0 0”, “0 0 0 1”, “0 0 1 1”, “0 1 1 0”, “0 1 1 1”, “1 0 0 0”, “1 0 0 1”, “1 1 0 0”, “1 1 1 0” and “1 1 1 1”. Figure 6 shows 11 possibilities of the three PR channel bits of the sub-track, when the PR channel bits of the track is “0 0 0 0”.

Figure 7 reveals the quasi-linear roll-off of the signal level when $pw$ = 80/40/130 nm. With the decrease of the $pw$, signal folding becomes more serious, meanwhile with the increase of the $pw$, the difference among the signal levels is smaller. Therefore, we choose the middle value, $pw$ = 80 nm.

Table 1 shows the channel bits parameter used in the MD optical disc, based on the BD characteristics. Then we can analyze the linear and non-linear characteristics of the signal of the MD optical disc.

### 3.3 Linear signal and non-linear signal analyze

According to Eqs. (10), (11) and (12), we can obtain the linear coefficient and non-linear coefficient. $c_j$ is just the linear coefficient of the PR, which can be calculated by Table 1 and Eqs. (4), (7) and (8). The value of $c_j$ is shown in Table 2.

Figure 8(a) shows nonlinear coefficient among the channel bits of the track, Fig. 8(b) shows nonlinear coefficient among the channel bits of the sub-track, and Fig. 8(c) shows nonlinear coefficient among the channel bits of the sub-track and track. Because the minimum distance between pits of the sub-track is 2 channel bits, there is not the term of “$j$ = 1”.

Figure 9 shows simulated signal waveform according to the model of a BD pick-up unit, which consists of linear approximation and nonlinear approximation. The solid line represents the full signal and the dotted lines represent linear approximation and nonlinear approximation separately. From Fig. 9, we can observe that the nonlinear contributions are very small in the center area of long land runs (5T and 11T) but are nonnegligible at the center of the

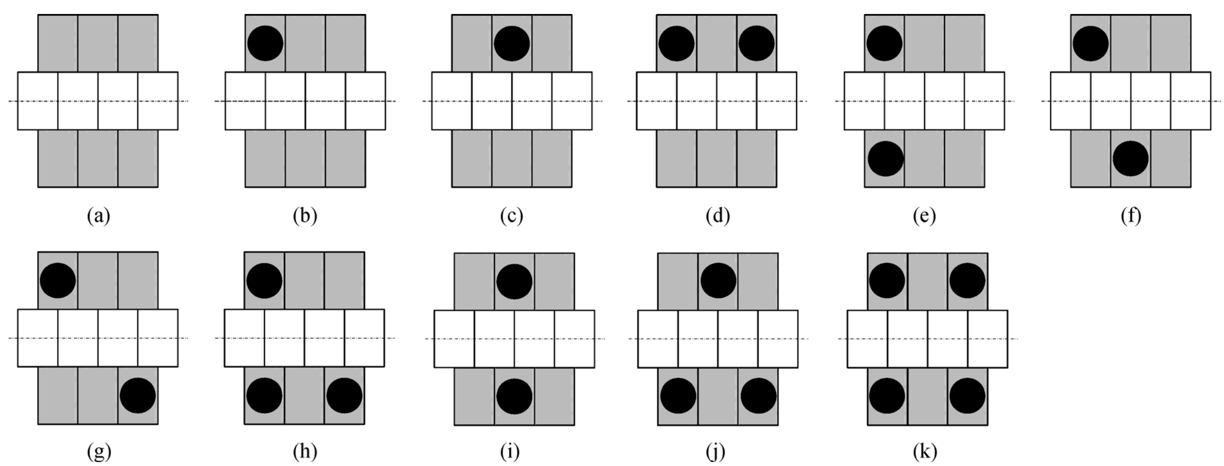


**Fig. 6** All possibilities of the partial response (PR) channel bits of the sub-track, when the PR channel bits of the track is “0 0 0 0”

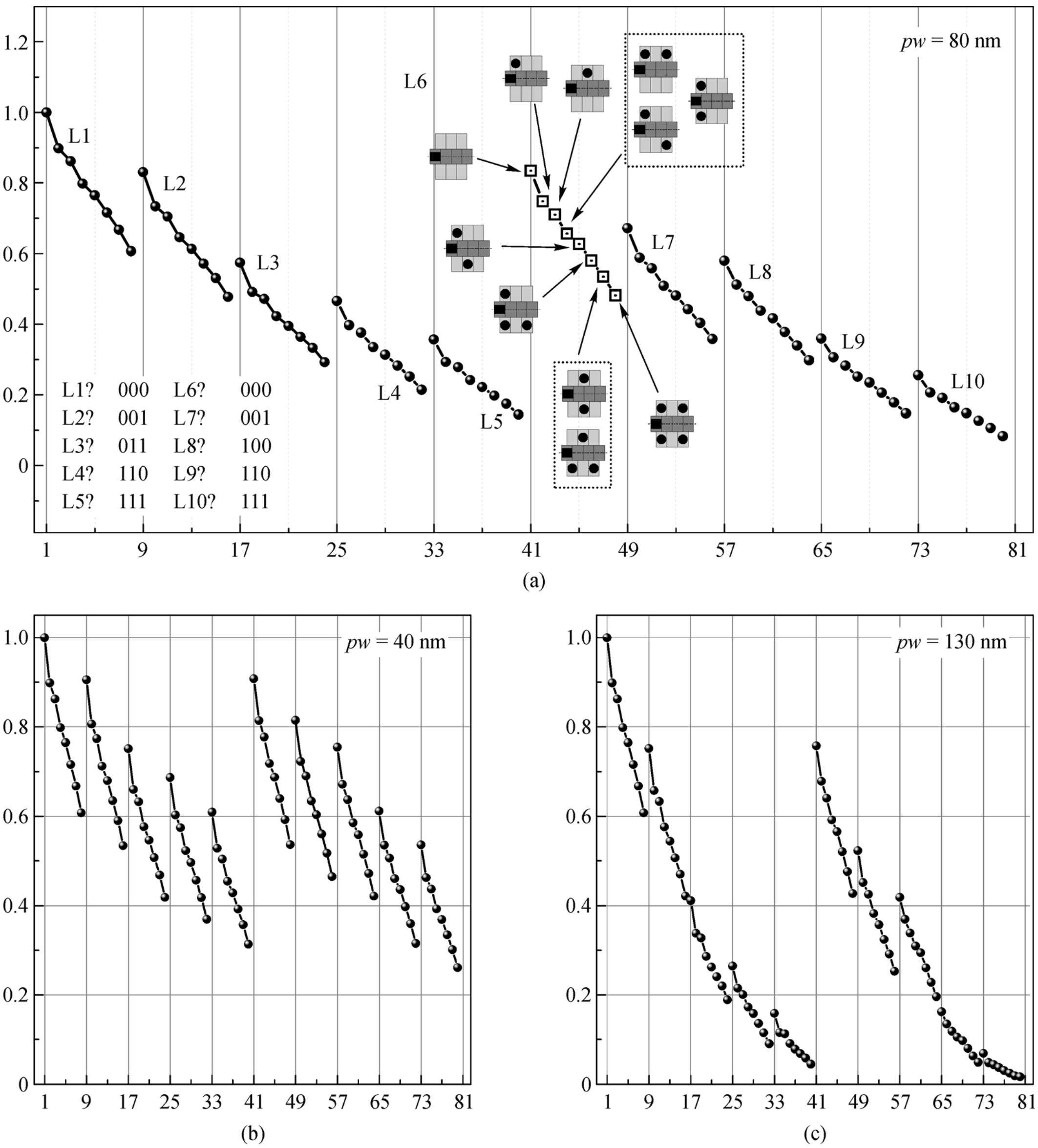


**Fig. 7** Signal patterns for the partial response (PR) channel bits. (a) Signal patterns for the PR channel bits, when *pw* = 80 nm. L(1,10) represent 10 signal pattern curves, and all 8 signal patterns in every signal pattern curve are obtained by the same PR channel bits of the track and different PR channel bits of the sub-track. The PR channel bits of the track in every signal pattern curve are shown. Correspond with all point of L6, all possibilities of the PR channel bits of the sub-track are shown. The several signal patterns in the dotted frame are merged into one point because of their similarity; (b) and (c) signal patterns for the PR channel bits, when *pw* = 40 and 130 nm

**Table 1** Channel bits parameter

| channel bitwidth /nm | channel bit length /nm | pit area width /nm | sub-track round diameter/nm |
|---|---|---|---|
| 130 | 90 | 80 | 80 |

**Table 2** Coefficients of partial response (PR)

| position | $j=1.5$ | $j=1.0$ | $j=0.5$ | $j=0$ | $j=-0.5$ | $j=-1.0$ | $j=-1.5$ |
|---|---|---|---|---|---|---|---|
| sub-track | | 3 | | 4 | | 3 | |
| track | 5 | | 9 | | 9 | | 5 |
| sub-track | | 3 | | 4 | | 3 | |

shortest land runs (2T and 4T). The nonlinear contributions are most significant in the center area of long pit runs, and their amplitude increases with increasing run length.

## 4 Experiments

In simulation experiment, the simulated full signal is processed by two-dimensional Viterbi detector. Figure10 shows the bit error rate (bER) performance with *chl* = 90 and 100 nm.

As the simulation result shown, the bER is zero with

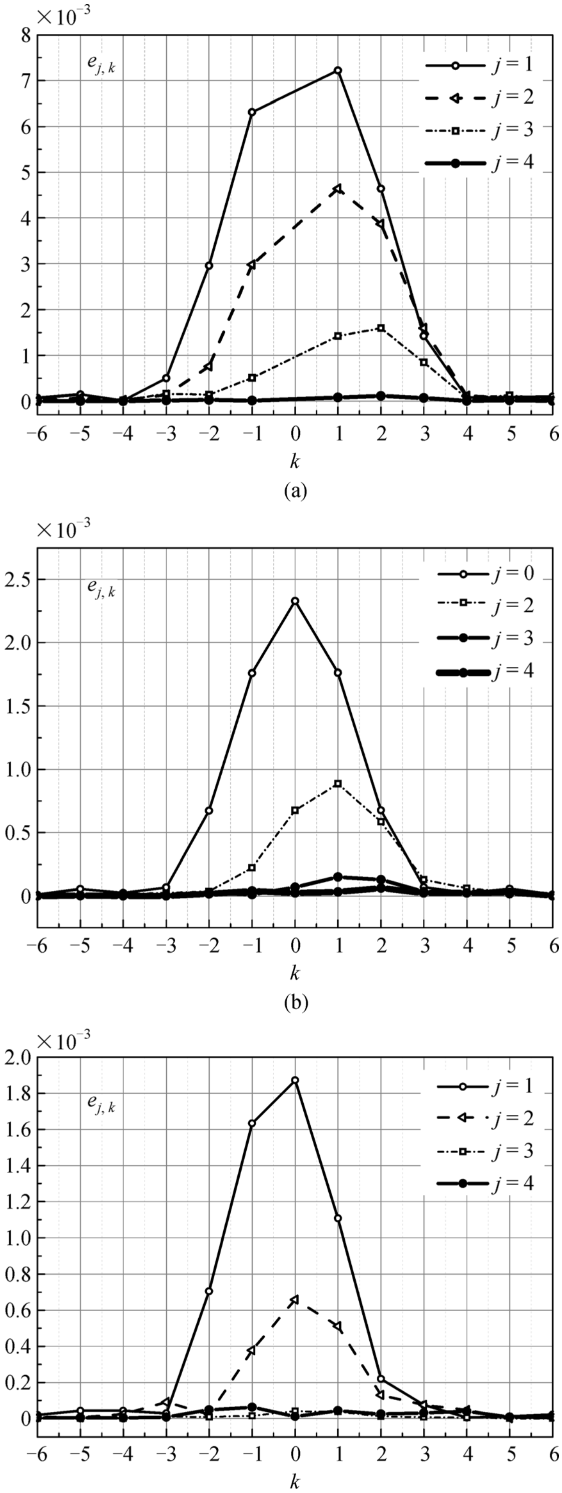


**Fig. 8** Nonlinear coefficient. (a) Nonlinear coefficient among the channel bits of the track; (b) nonlinear coefficient among the channel bits of the sub-track; (c) nonlinear coefficient among the channel bits of the sub-track and track

SNR is 0 dB. With the same signal to noise ratio, the shorter the channel bit length, the higher the bER. In both

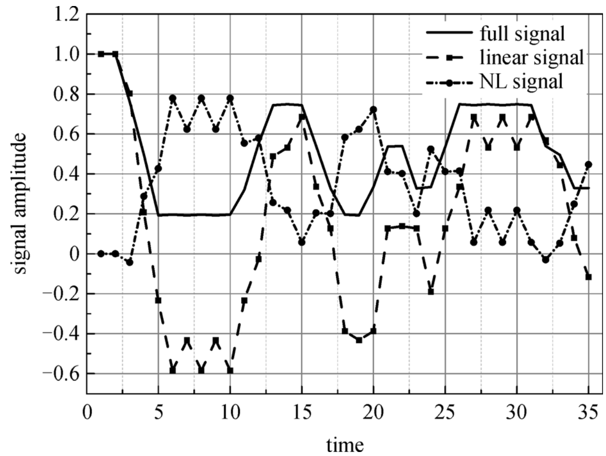


**Fig. 9** Simulated signal waveform according to the model of a BD pick-up unit ($\lambda$= 405 nm, NA = 0.85). Channel bit length, *chl* = 90 nm; channel bit width, *chw* = 130 nm. The channel bit sequence of the track is -8T-4T-4T-2T-2T-8T-, and the channel bit sequence of the sub-track is comprised only by 2T. The full signal waveform, the linear approximation (with constant term 1 and the linear contributions with $c_j$), and the nonlinear (NL) contributions related to $e_{j,k}$

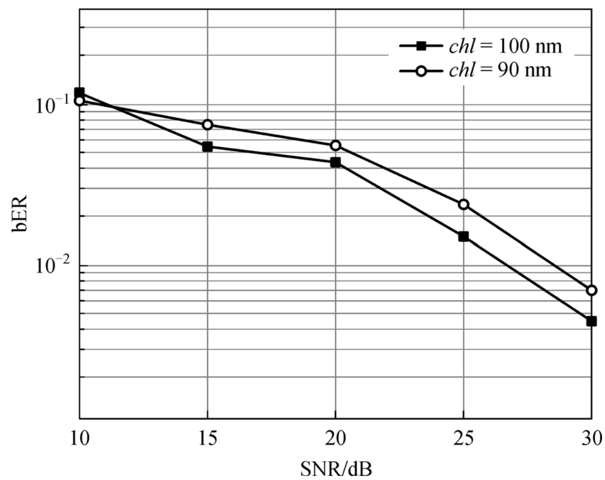


**Fig. 10** Comparison of bER performances for different *chl*

cases, with the SNR is 30 dB, the bER can reach $10^{-3}$. The bER can meet the needs of optical storage system. Meanwhile, the feasibility of the novel multi-dimensional optical storage is verified.

## 5 Conclusions

A novel multi-dimensional optical storage has been presented. The basic storage theory of the MD optical disc has been shown. Utilizing the scalar diffraction model and nonlinear signal-processing model, we choose the proper channel bits parameter for BD pick-up unit ($\lambda = 405$ nm, NA = 0.85), and analyze the linear and nonlinear characteristics of the signal waveform of the MD optical disc. With the same physical parameters of the optical readout system, the density of MD optical disc can be increased by 2 times over the traditional disc, and for the first format of MD optical storage, the readout rate can be increased by 10 times over the traditional disc. Meanwhile, the MD optical storage is compatible with the traditional optical storage. Because the structure of the track is retained, the servo in readout system of MD optical disc is the same as the traditional disc. In the readout system of MD optical disc, improved PRML is used to decrease ISI. In simulation experiment, the simulated full signal is processed by two-dimensional Viterbi detector. With the SNR is 30 dB, the bER can reach $10^{-3}$. The bER can meet the needs of optical storage system. Meanwhile, the feasibility of the novel multi-dimensional optical storage is verified.

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