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Optical disc writing strategy for analog signal recording

Kimihiro Saito[1]

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Abstract
Optical discs are being sought as low-cost, earth-friendly storage candidates in response to increasing data volumes. To increase the recording density of optical disc, analog recording technique such as the Orthogonal Frequency Division Multiplexing (OFDM) method has been investigated. Since bitwise information is recorded on optical discs, it is necessary to create a column of marks corresponding to the analog signal for the OFDM method. The Delta-Sigma Modulation (DSM) is known as an analog to digital conversion method in the area of audio. This method transfers efficiently an analog signal to a binary sequence with a simple circuit. In this paper, the application of the method for analog signal recording and the simulation results of the mark recording process on the optical disc are described. The optical disc recording utilizes temperature rise of a multilayer film stack in recording process that is triggered by light focusing. A simplified, 2.5-dimension, thermal analysis is applied to do the large-scale simulation of recording mark sequence.

1 Introduction

As the huge amount of data increase, earth friendly and low-cost storage system is required [1]. Optical disc systems are candidate to achieve such data storage systems. Optical discs such as BD™, BDXL™ [2, 3] and AD [4] discs are currently demonstrated in the market. These discs use phase change materials and employ the partial response maximum likelihood (PRML) [4–9] method for signal processing. The class IV partial response signaling for data detection was first applied to magnetic recording [10–14].

To further increase the recording density of optical disc, analog recording technique such as the Orthogonal Frequency Division Multiplexing (OFDM) [15–19] method has been investigated. In the application of the OFDM, the data sequence is separated in a set of frequency sub-bands and then recorded on the disc. Defocus and disc tilt cause deformation of optical transfer function. Since the deformation changes only the amplitudes of the information sub-bands, they can easily be recovered.

The information data is recorded bitwise as a mark sequence on optical disc systems. Therefore, the analog signal generated by the OFDM method should be converted to a binary signal. I tried to use the Delta-Sigma Modulation (DSM) [20, 21] that is known as an analog to digital conversion method in the area of audio. This method transfers efficiently an analog signal to a binary sequence with a simple circuit.

The recording marks and readout signal using the OFDM and the DSM method are computer simulated with an optical pickup and recording medium. A sequence of large number of marks is necessary to evaluate a signal quality for the calculation. In addition to it, the recording medium consists of a multilayer stack of dielectric, recording and heat sink materials. The conventional three-dimensional thermal calculation methods [22, 23] need huge computational cost for the simulation. I tried to make a model of the simplified, 2.5-dimension, thermal analysis and applied to the simulation of mark formation process.

Using the modulation and the simulation method, the recorded column of recorded marks and then the readout signal was derived. Because of the non-linearity of the processes, a non-linear filter was utilized for signal equalization.

✉ Kimihiro Saito
ksaitoh@ktc.ac.jp

1 Department of Comprehensive Engineering, Kindai University Technical College, Nabari, Mie 518-0459, Japan

2 Optical disc recording with OFDM method

Readout channel of optical disc systems has a limited spatial frequency band determined by the wavelength and the numerical aperture of the objective lens. Sometimes defocus and disc tilt cause deterioration of the Modulation Transfer Function (MTF) of the optical discs as shown in Fig. 1.

The data signal is separated in several frequency bands by the OFDM method, as illustrated in Fig. 2. In each sub-band, the separated information data is represented by the amplitude and the phase of a sine wave with the Quadrature Amplitude Modulation (QAM) method. The sum of the sub-band signals creates the whole analog signal, as shown in Fig. 3.

In that case, the deterioration of the MTF only affect as amplitude decays of the sub-band signals. The amplitude decreases can be easily recovered by the gain of the electrical circuit. This advantage of the OFDM method, compared to the conventional PRML readout, was described in the reference 19.

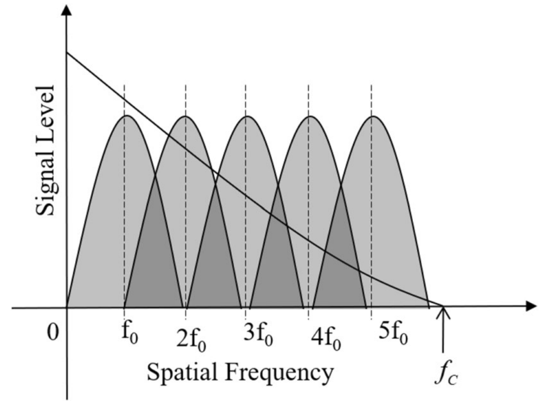

Fig. 2 Sub-bands arrangement used for the OFDM method applied to optical disc systems

3 Analog recording method using DS modulation

Since the OFDM generates an analog signal, a different optical recording scheme should be adopted for the conventional bitwise recording. There is another reason that the laser diode has non-linear and threshold characteristics of light intensity modulation. As for the analog to digital signal conversion method, the DSM method is firstly introduced by Inose et al. [20]. The simple circuit as shown in Fig. 4 transforms an analog signal to a pulse width modulation (PWM) signal. Using the digital signal for the light intensity modulation in an optical pickup, binary marks corresponding to the original analog signal can be created on the optical recording media. To determine the PWM signal, the input signal is normalized by its standard deviation. In addition to that, the offset and gain should be adjusted. Because the recorded marks have binary characteristics, high frequency of the analog signal is enhanced with a filter.

4 Optical recording simulation with a simplified thermal analysis

In optical recording process, the marks are created as reflectance changes by heating the recording medium with a focused light spot. To obtain high reflectance contrast and control recording sensitivity, a multilayer structure is employed for recording media. To simulate the recording method described above, opto-thermal analysis is necessary

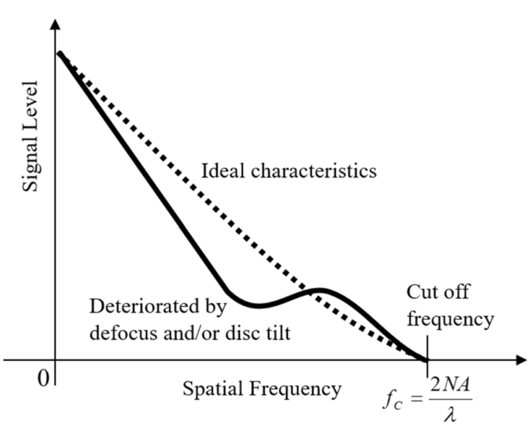

Fig. 1 Deterioration of the MTF caused by disturbances of optical disc system

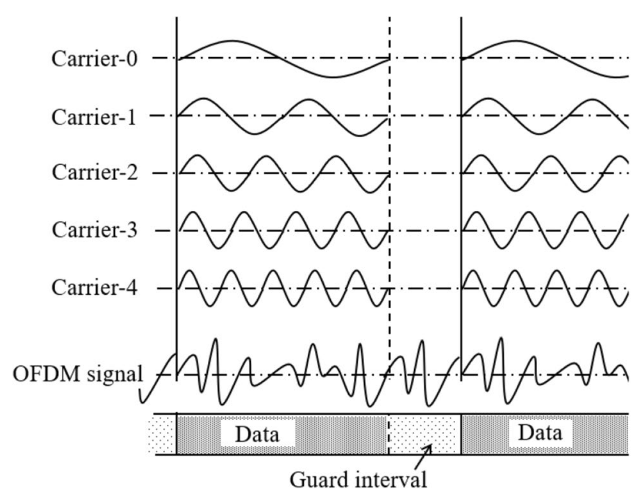

Fig. 3 Analog signal generated by the OFDM method

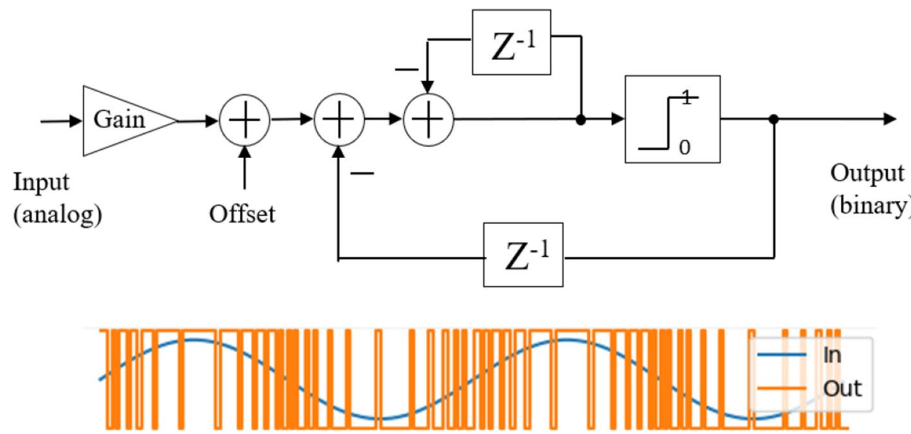

Fig. 4 Block diagram for the DSM signal generation

to confirm the mark forming process with the PWM light modulation.

To do such simulation, three-dimensional finite element or finite difference time domain method are often used. However, they cost huge computational time and resources, because it is necessary to obtain the readout signal from more than a thousand of the wavelength range. So, we need a simple calculation method.

There are the simple and typical solutions as the impulse responses for two- and three-dimensional heat propagation problems applied to homogeneous media [24]:

$$\text{Two-dimensional case}: \frac{1}{8\pi D\cdot t}e^{-\frac{|\mathbf{r}^2|}{4D\cdot t}}, \quad \mathbf{r}=(x,y), \tag{1}$$

$$\text{Three-dimensional case}: \frac{1}{(8\pi D\cdot t)^{\frac{3}{2}}}e^{-\frac{|\mathbf{r}^2|}{4D\cdot t}}, \quad \mathbf{r}=(x,y,z), \tag{2}$$

where t indicates time and D is the diffusion coefficient.

The idea to apply these solutions for a multilayer structure is based on the assumptions below.

1. Only the function of x–y plane at the recording layer (constant z) is enough for simulation.
2. The multiplication factor and the exponential factor related to time t are expressed as functions of t, that is

$$f(t)\cdot e^{-\frac{|\mathbf{r}^2|}{D(t)}}, \quad \mathbf{r}=(x,y). \tag{3}$$

To confirm the above method, I used the model of recording media structure described in the Ref. [24], which is shown in Fig. 5.

At first the impulse response on the recording layer was calculated using the two-dimensional finite differential method with a lattice of cylindrical coordinate. The calculation cost is very low because of the two-dimensional

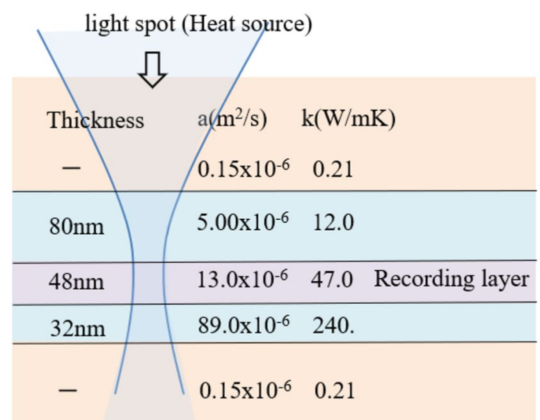

Fig. 5 Recording media model of the multilayer structure and the constants for the simulation. "a" and "k" denote the thermal diffusivity and the thermal conductivity of the media, respectively

configuration. As a heat source, a narrow gaussian light spot was irradiated in the medium at $t=0$ and then quickly turned off. The time dependencies of the gaussian peak and base by heat dispersion were calculated. The factors of multiplication and exponential parts of the impulse response (3) are indicated in Fig. 6.

The temperature profile T at time t is calculated as the convolution of the heat source and the impulse response:

$$T(\mathbf{r},t)=\int\int\frac{1}{C}P(\mathbf{r}')I(t')\cdot f(t-t')e^{-\frac{|\mathbf{r}-\mathbf{r}'|^2}{D(t-t')}}\,d\mathbf{r}'dt', \tag{4}$$

where the light distribution on the recording layer is expressed as

$$P(\mathbf{r})=P_0\cdot\frac{1}{2\pi|\mathbf{r}_0|^2}e^{-\frac{|\mathbf{r}|^2}{2|\mathbf{r}_0|^2}}, \quad \mathbf{r}=(x,y) \tag{5}$$

and $I(t)$ is the writing pulse sequence taking 0 or 1. "C" is the heat capacity (unit: J/K) and "P_0" is the peak power (unit: W) of the light pulses. The gaussian shape for the light

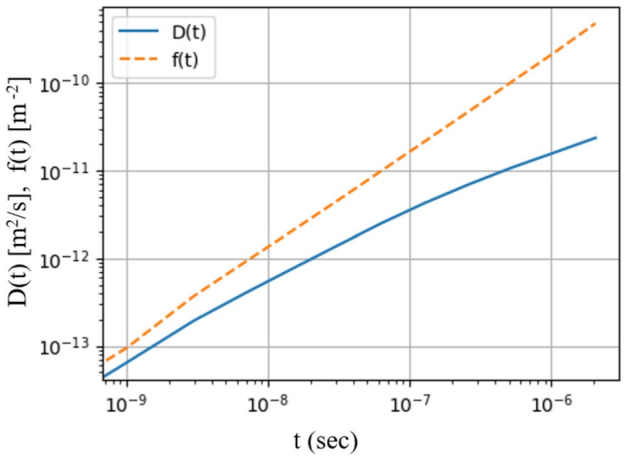

Fig. 6 Time dependencies of the multiplication and the exponential factors of the impulse response

spot is assumed. So, $|\mathbf{r}_0|$ equals to 0.52 times the radius of the Airy disc (λ/NA).

This method was confirmed by comparing the calculated temperature profile reported in the reference 24. This method is not fully three-dimensional calculation but employing three-dim. information through the functions $D(t)$ and $f(t)$. So I call it "2.5-dimensional thermal analysis" in this paper.

While the light spot is tracing the recording track with the writing pulse sequence, the maximum temperature profile is updated. The areas of the recorded marks are determined as where the maximum temperature beyond the threshold level.

5 Optical readout simulation and signal evaluation

After determined the areas of the recorded marks, the readout signal is calculated. I used the simple model of the convolution of the light spot intensity, the Point Spread Function (PSF), and the mark patterns [25]. In this calculation, the Airy pattern was used as the ideal case of the PSF:

$$S(t) = \int \mathrm{PSF}(x - vt, y)\mathrm{Marks}(x, y)\mathrm{d}x\mathrm{d}y \quad (6)$$

$$\mathrm{PSF} = P_0\left(\frac{J_1(\tilde{r})}{\tilde{r}}\right)^2, \quad \tilde{r} = \frac{2\pi \mathrm{NA}}{\lambda}\sqrt{x^2 + y^2}, \quad (7)$$

where λ is the wavelength of the light source and NA is the numerical aperture of the objective lens, as shown in Fig. 7. The function Marks(x,y) takes 1 within the created marks and 0 otherwise.

Although the optical readout characteristics is linear, the readout signal has non-linear characteristics for the recorded signal, which is caused by the recording process.

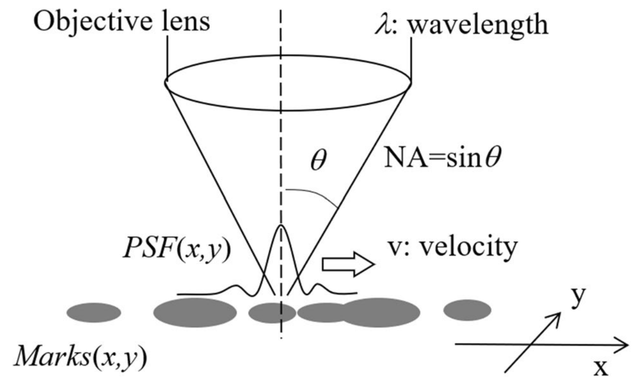

Fig. 7 Optical readout model used in the simulation

To compensate the signal distortion, the second-order adaptive filter, Volterra filter, was applied:

$$S_\mathrm{O}(n\tau) = \sum_{i=-N}^{N}\sum_{j=-N}^{N} A_{i,j}S_\mathrm{I}((n+i)\tau)S_\mathrm{I}((n+j)\tau) + \sum_{i=-N}^{N} B_i S_\mathrm{I}((n+i)\tau) + C, \quad (8)$$

where S_O, S_I and τ are output signal, input signal and sampling time.

Finally, the signal quality was evaluated using the normalized root mean square (RMS) value of the difference between the filtered signal and the recorded signal. And the RMS value was compared to that of the conventional bitwise recording case.

6 Simulation results

The parameters used in the simulation are listed in Table 1. To verify if the proposed DSM-based writing strategy works, the conventional bitwise and the OFDM recording cases were simulated and compared.

The whole system model used in this study is illustrated in Fig. 8. The reference signals from the information data passes the pre-enhance filter and then input to DSM circuit. The light pulse sequence is generated and then it drives the light source. The focused light spot on the disc creates reflectance marks on a rotating disc. After that, the readout signal from the optical pickup is filtered by a non-linear adaptive filter and evaluated.

6.1 Optical recording conditions

I used the known model for the recording media described in the reference 25 so as to confirm the proposed calculation model. The optical pickup model and the recording density were adopted to the recording media model at that time. Currently BD is the popular standard for a commercial optical data storage. The wavelength, NA, minimum

Table 1 Parameters for the simulation of bitwise and analog recording

Recording method	Bitwise	Analog (OFDM)
Wavelength	780 nm	780 nm
NA	0.5	0.5
Linear velocity	10 m/s	10 m/s
Recoding media	Figure 5	Figure 5
Threshold temp.	135 °C	116 °C
Modulation	(1,7)RLL	OFDM, 5 channels
Detection	PR(12221)	64-QAM
Clock	245 nm	Block size 8.09 μm
Readout sampling	245 nm	245 nm
Bit density	366 nm/bit	270 nm/bit
Pre-enhance	20 dB boosting at 700 lp/mm	
DSM gain	0.2	0.2
DSM offset	0.55	0.55
Peak power	8 mW	8 mW

mark length (two-clocks) of 405 nm, 0.85, and 150 nm are standardized, respectively. Since the optical resolution is determined by spot size λ/NA. The sampling clock 75 nm = 150 nm/2 of BD™ is translated to 245 nm for this simulation. The BD's recording bit density of 112 nm/bit is translated to 366 nm/bit for this simulation. For the PRML data detection, class (1,2,2,2,1) is employed to generate the reference signal.

The same sampling clock length of 245 nm was employed for the OFDM simulation. The block size is 33 clocks. The data area and the guard interval are 29 and 4 clocks, respectively. The total bits in a block is calculated to 6 bits × 5 channels = 30 bits considering 64-QAM. Thus, the recording bit density is 270 nm/bit for the OFDM simulation.

The reference signals of the bitwise and the OFDM simulation are indicated in Fig. 9a, b.

6.2 Writing pulse generation

As described in Sect. 3, the reference signals are pre-enhanced with the high-pass filter shown in Table 1. After that, the signals are input to the DS modulation circuit. The light source in the optical pickup is driven by the PWM signals that are adjusted to give the range of zero to the peak power on the recording medium. Figure 10a, b shows the pre-enhanced signals and the writing pulses generated by the DS modulation circuit.

6.3 Temperature profiles and marks created by the DSM recording

Figure 11a, b presents the calculated maximum temperature profiles of the bitwise and the analog recording cases. Figure 12a, b are the cross sections along the track center. The profiles already show non-linear characteristics. Figure 13a, b is the simulated results of recorded marks. The marks are defined as the areas,where the maximum temperature beyond the threshold level. Even for the OFDM recording case, the created marks are separated. The threshold temperature for the OFDM recording is lower than that for the bitwise case as shown in Table 1. It was resulted by the optimization of the readout signal quality. It is considered that the analog signal of OFDM requires larger dynamic range.

6.4 Readout signals

The readout signals for the bitwise and the analog recording cases are indicated in Fig. 14a, b. The outputs of the non-linear adaptive equalizer and the reference signals are shown in Fig. 15a, b. Because of the non-linearity in the recording process, the directly observed signals are distorted. To compensate them, the non-linear filter with $N = 10$ as described in Sect. 5 works well. The normalized root mean square of the difference between the direct and

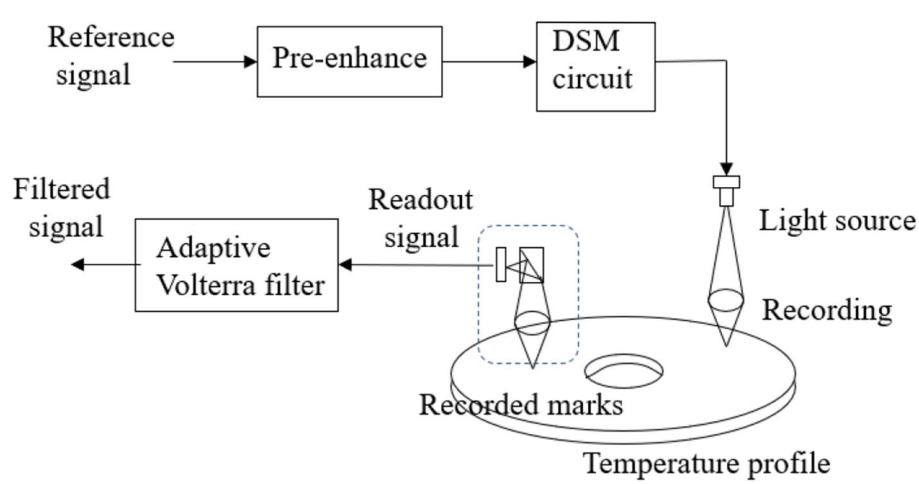

Fig. 8 Whole system diagram used in the simulation

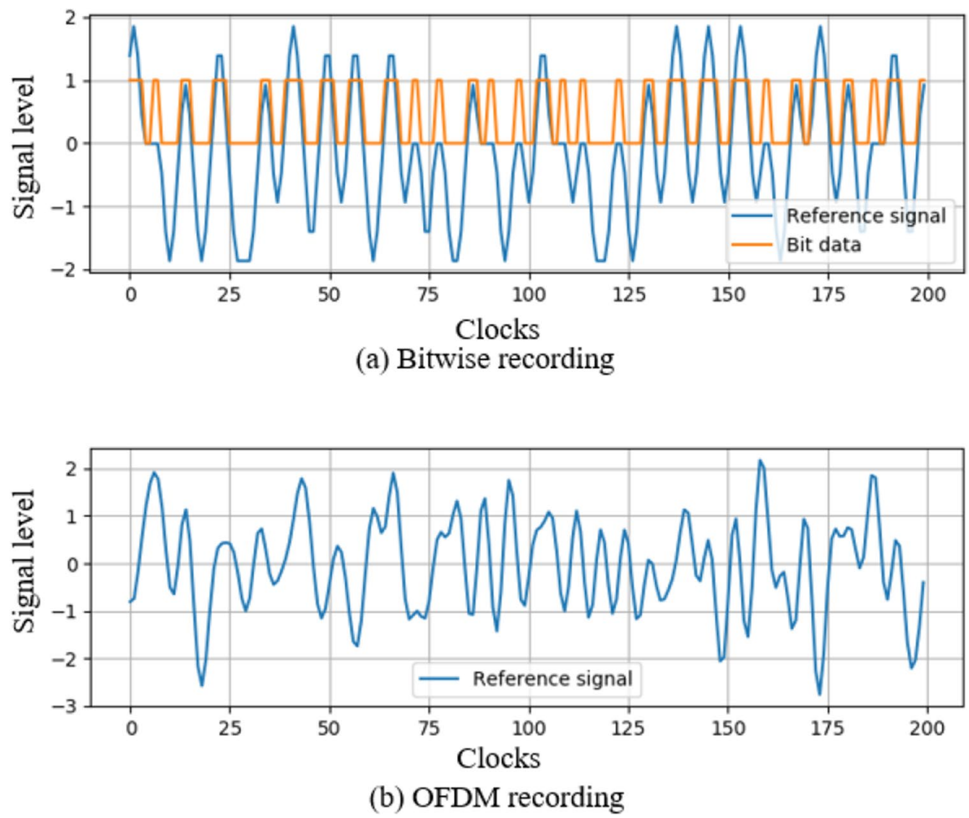

Fig. 9 Examples of the reference signals of **a** bitwise and **b** OFDM recording, respectively

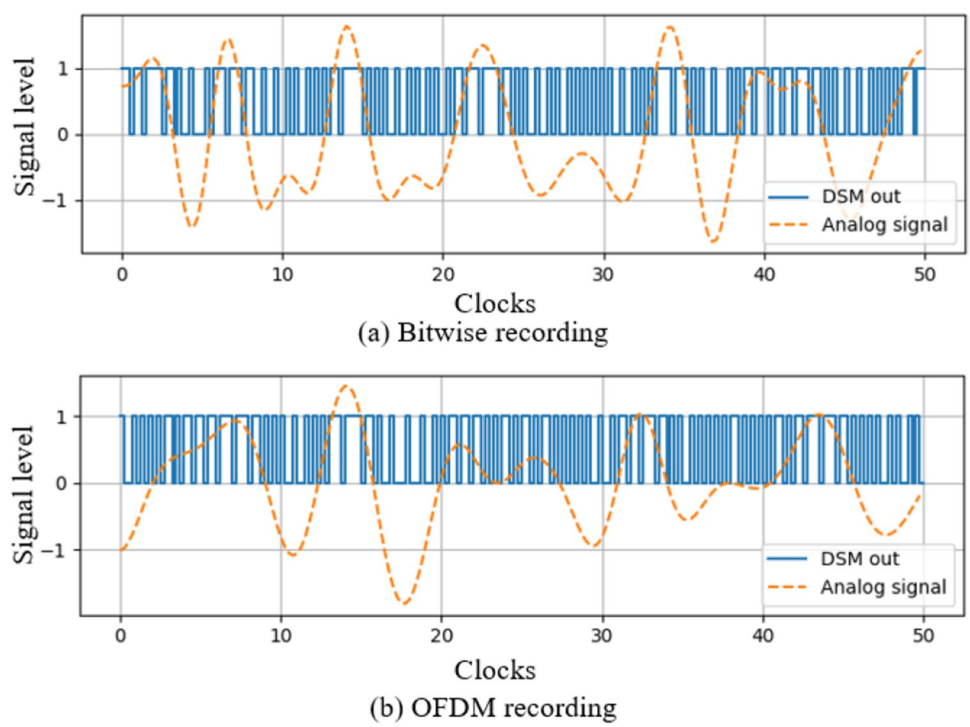

Fig. 10 Generated DSM signals from the enhanced reference signals

filtered readout signals for the conventional bitwise recording are 41.8% and 25.7%, respectively. The RMS difference values for the OFDM recording method are 52.5% and 29.7% for direct and filtered readout signals. When A’s in (8) are set to zero, the RMS values of linear filter cases are 33.9% and 43.7% for the bitwise and the OFDM cases, respectively. It means that non-linearity is certainly existing and can be compensated by the proposed filter.

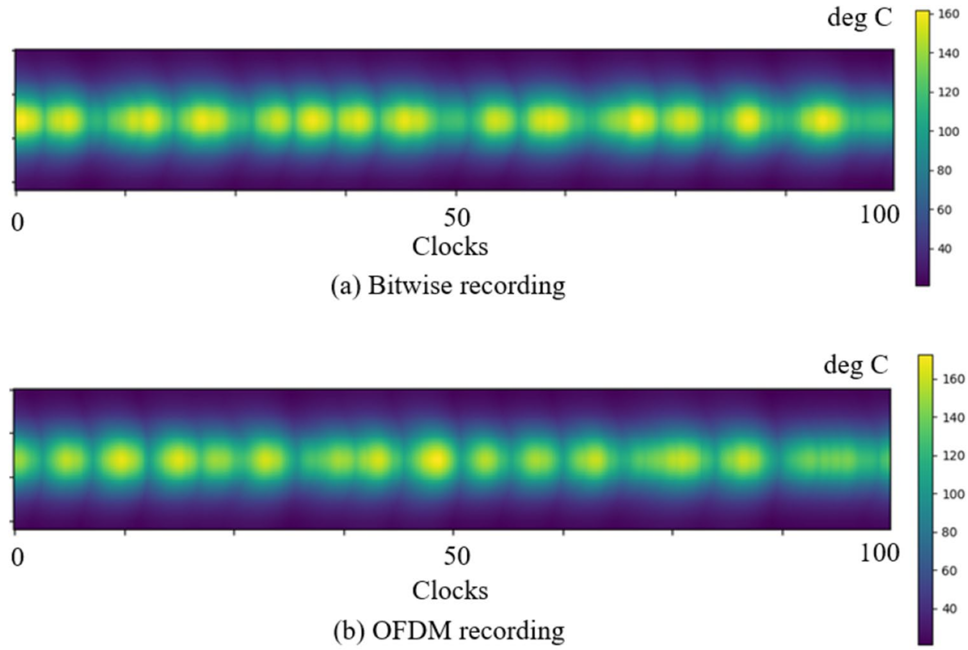

Fig. 11 Calculated maximum temperature profiles of the bitwise and the OFDM recording

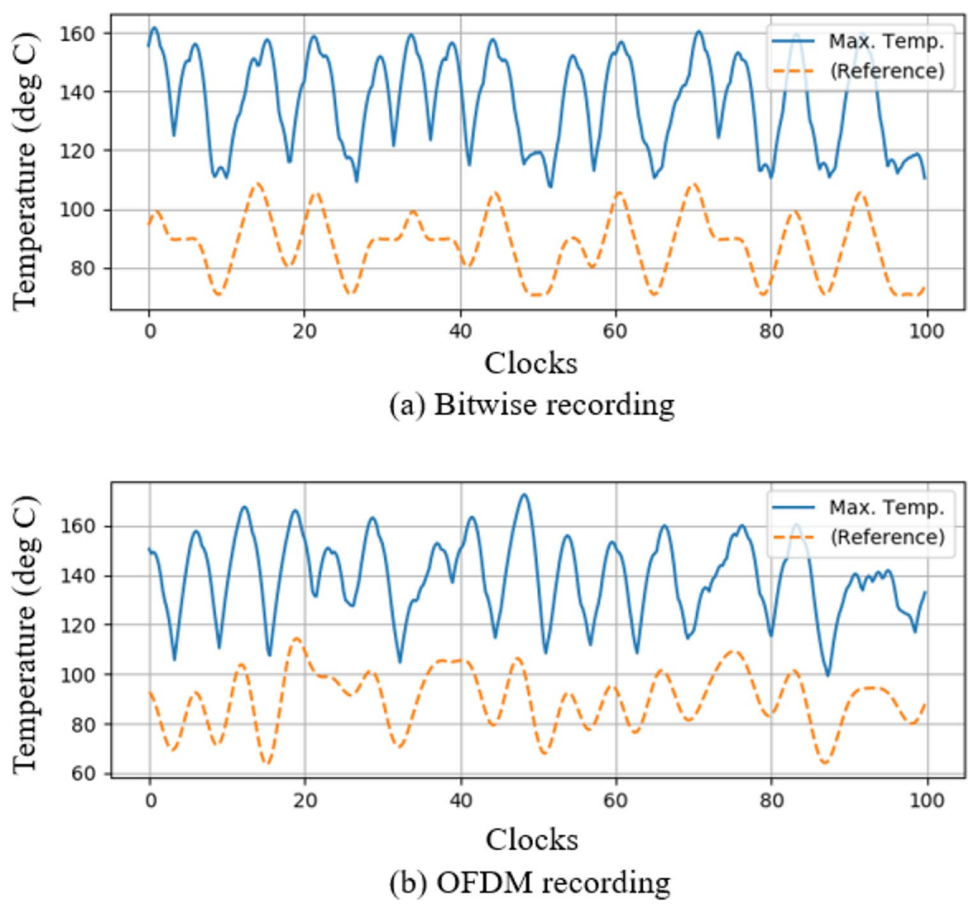

Fig. 12 Cross sections of the maximum temperature in the cases of bitwise and OFDM

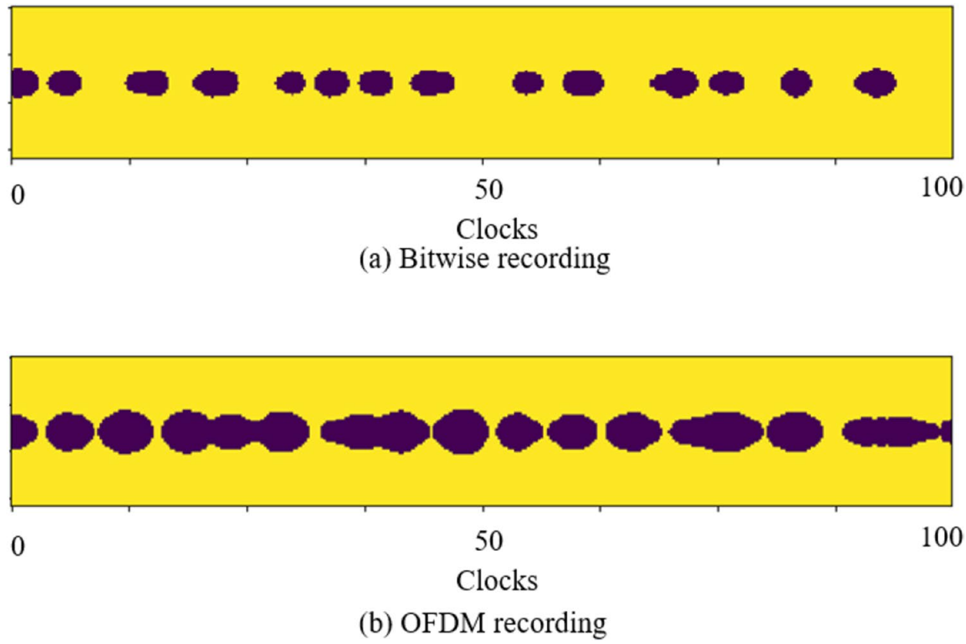

Fig. 13 Simulated marks by thresholding of the maximum temperature profiles

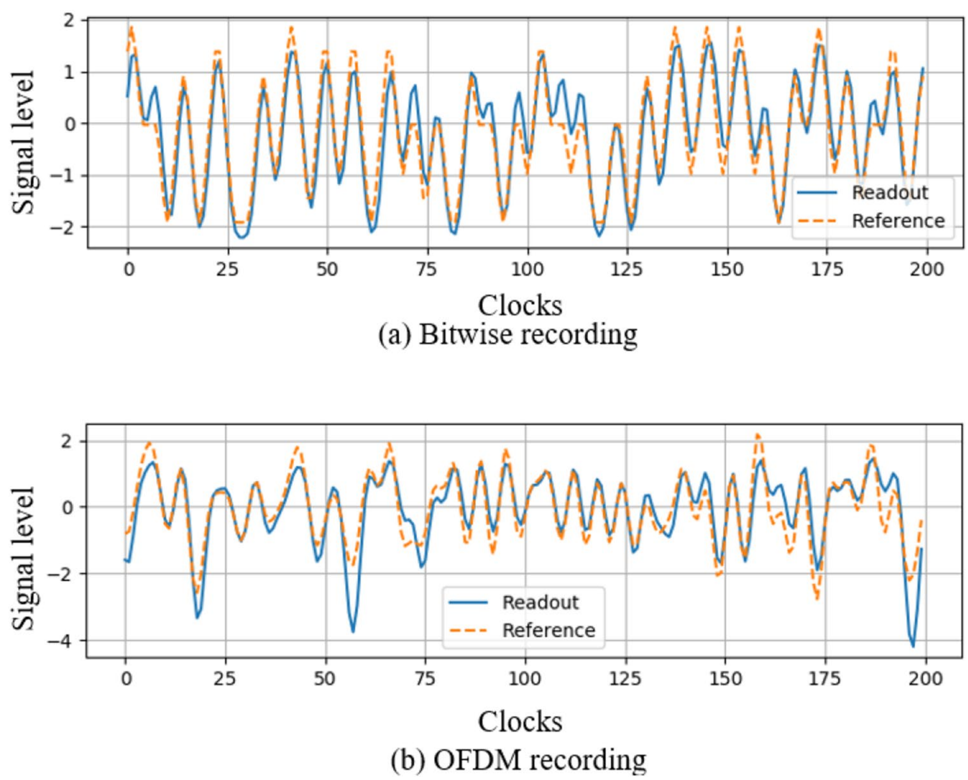

Fig. 14 Simulated readout signals from the optical pickup

For comparison, readout signal from rectangular bitwise mark model was calculated. The RMS difference value was about 6% in that case. It is thought that there is a room for improvement and parameter tuning in this method.

7 Conclusions

The advantages of analog recording technique using the OFDM method for optical disc systems are described. This application allows us to expect robustness against

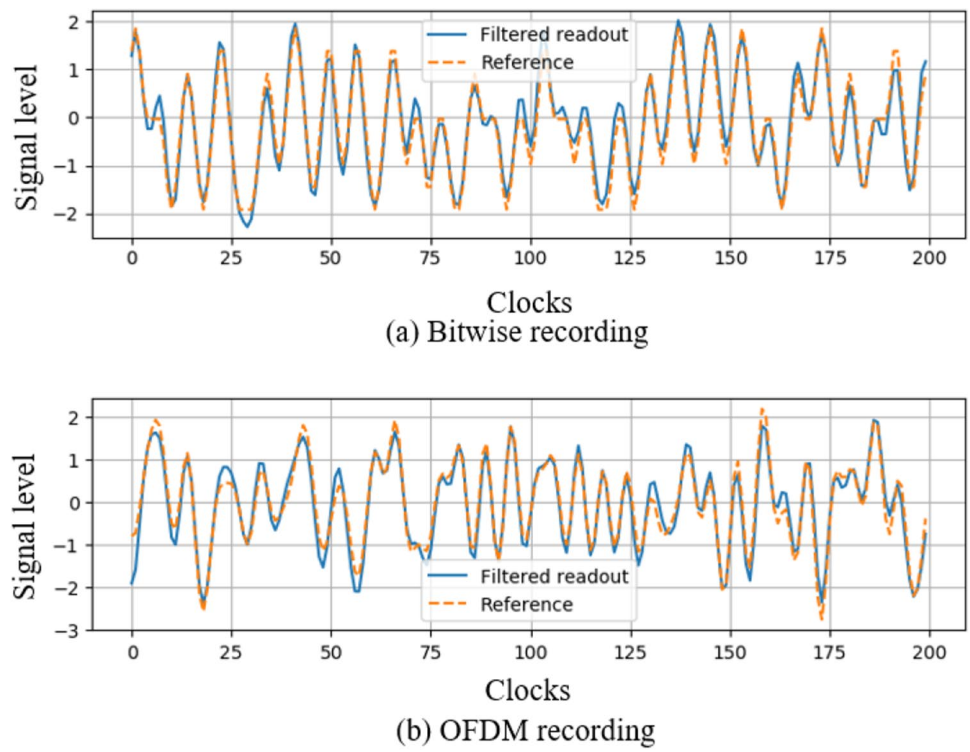

Fig. 15 Compensated signals using the non-linear filter

the practical disturbances such as defocus and disc tilt because of the sub-band separation scheme. To achieve the analog recording on optical disc media, the DSM method is applied to generate write pulse signal from the reference analog signal. The opto-thermal-analysis based computer simulation shows that the piecewise recorded marks are possible to generate analog readout signal, which is created by the DSM output signal. The readout signal has non-linear characteristics but can be compensated using a second-order adaptive filter.

Using a functional time dependent constants model, a 2.5-dimensional opto-thermal simulation method is introduced. Once calculated the impulse response of the dispersion equation for the multilayer structure, long sequence of the recorded marks can be computer simulated inexpensively.

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