FTN method applied to OFDM for optical disc signal readout

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Abstract

To increase the recording density of optical discs, analog recording techniques such as the use of orthogonal frequency division multiplexing (OFDM) method has been investigated. In OFDM method, the recording signal is separated into several sub frequency bands. So the readout channel becomes tolerant of the deterioration by disturbances such as defocus and disc skew in optical disc systems. Faster than Nyquist (FTN) signaling is known as the method to increase the transfer rate of OFDM channels in the area of telecommunication. In this paper, a possibility to achieve higher recording density of optical disc systems by applying the FTN is described. The readout signal of FTN-OFDM method was calculated using the optical disc readout and the signal processing models considering the crosstalk from adjacent tracks and FTN applied to a five-channel 64-QAM OFDM system. The calculation results show that the proposed system has a possibility of 1.5 times recording density of the conventional optical disc with a similar tolerance to disturbances.

1 Introduction

In response to the increase of data volumes, there is a demand for huge capacity and environmentally friendly data storage such as optical disc systems. The telecommunication technologies become more important and sometimes applied to the storage systems. The fifth generation (5G) technology [1] for cellular phones has been deployed worldwide, which aims at providing us of up to 10 Gbps speed by radio waves. One of the key technologies of the 5G is called non-orthogonal multiple access (NOMA) [2] that is able to break through the bandwidth limit of the conventional orthogonal frequency division multiplexing (OFDM) [3–5]. Moreover a technique to exceed the 5G bandwidth has been studied, which is known as faster-than-Nyquist (FTN) [6, 7] for the improvement of the OFDM.

The current optical disc system such as BDXL™ [8, 9] and Advanced Disc (AD™ [10]) adopted bitwise recording in which the data is written as a sequence of binary reflectance changes on the recording layer of the discs. To realize optical disc systems using OFDM, analog recording method

using delta-sigma modulation method has been introduced [11, 12]. In this study, I introduce the improvement of the OFDM recording/readout method for optical disc systems by using FTN method and show the simulation results. In Ref. [13], it is shown that the OFDM method is capable of disturbances coming up to optical disc readout systems, such as defocus and radial/tangential disc skews. The simulation results show that the proposed method is also capable and brings an increase of the recording density for the future optical data storage.

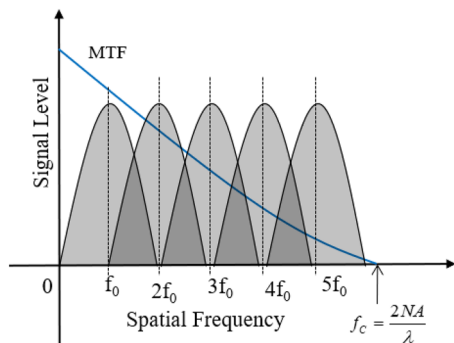## 2 The readout model of optical disc readout

A simple model of signal detection in an optical disc system [14] is shown in Fig. 1. The light source focused on the plural tracks allows us to achieve a high optical recording density. The detected signal contrast is calculated as the integrated light intensity of the point spread function (PSF) multiplied with the reflectance distribution of the marks on the disc. I used the scaler diffraction theory. The PSF is the light intensity distribution on the disc, which is calculated as the square amplitude of the Fourier transform of the light amplitude distribution on the objective lens. The readout signal consists of several sequences that are the convolutions of the impulse responses and the recorded marks on the different tracks. The impulse response corresponding to

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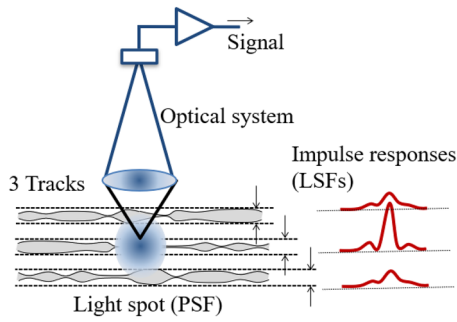
Fig. 1 A simple model for optical disc signal readout using line spread functions
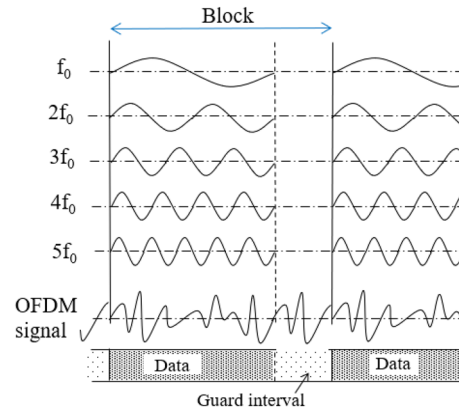

Fig. 2 MTF of an optical disc system and an assignment of subbands for OFDM readout method

Fig. 3 An OFDM signal block and recording signal including guard intervals

Fig. 4 Schematic of the modulation process of OFDM method with 5-subband signal
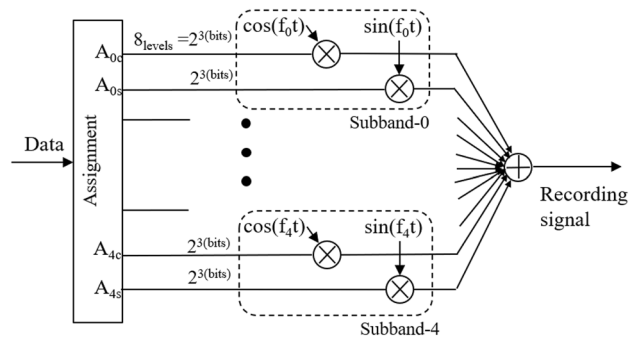
each track is calculated as the line spread functions (LSF) that are integrated PSFs along the width of recorded marks. The modulation transfer function (MTF) is derived from the Fourier transform of the LSF. I used three impulse responses of the center and the adjacent tracks in this study. Since the recorded marks of the OFDM signal are not bitwise, grayscale reflectance was assumed in the calculation model. To perform the simulation of practical situations in optical disc drive operations, disturbances of defocus and disc tilt of tangential and radial directions were modeled as wavefront aberrations on the pupil function of the optical pickup, which cause distortion of the PSF.

3 OFDM method applied to optical disc readout

Readout channel of an optical disc system has a limited spatial frequency band determined by the wavelength and the numerical aperture of the objective lens. A typical shape of

MTF of an optical disc system is shown as the line in Fig. 2. The data signal is separated in several frequency bands by the OFDM method as illustrated in the figure.

The bandwidth of the subbands is determined by the block size of the modulated signal. Figure 3 shows the schematic of the block. Each subband is formed by carrier signals, i.e. cosine and sine signals, and their amplitudes are modulated. The schematic of the modulation process is shown in Fig. 4. In this case, 10 amplitudes = 5 subbands × 2 (cosine and sine), i.e. $(A_{0c}, A_{0s}, ..., A_{4c}, A_{4s})$, are assigned from the streaming bit data. The guard interval (GI) [15] is necessary for suppressing the intersymbol (block) interference and for synchronization.

The separation of the amplitudes from different subbands and cosine/sine carriers is based on the relationship:

$$\frac{2}{T}\int_{t=0}^{T}\left\{\begin{array}{c}\cos(2\pi nt/T)\\\sin(2\pi nt/T)\end{array}\right\}\cdot\left\{\begin{array}{c}\cos(2\pi mt/T)\\\sin(2\pi mt/T)\end{array}\right\}dt=\left\{\begin{array}{ll}1: & n=m\\ & \cos\cdot\cos\ \text{or}\ \sin\cdot\sin.\\0: & \text{otherwise}\end{array}\right. \quad (1)$$

In the demodulation process, the amplitudes of the carriers are obtained by the synchronous detection that is the integration of the mixing signal with the carrier. The detected amplitudes are indicated by the constellation map as described later. In each sub-band, the separated information data are represented by the amplitudes of sine and cosine wave components according to the quadrature amplitude modulation (QAM) method [4]. The 64-QAM is applied to each subband in this study. All the subbands should be within the cut-off frequency of the optical readout system. The sum of the sub-band signals creates the whole analog signal as shown in
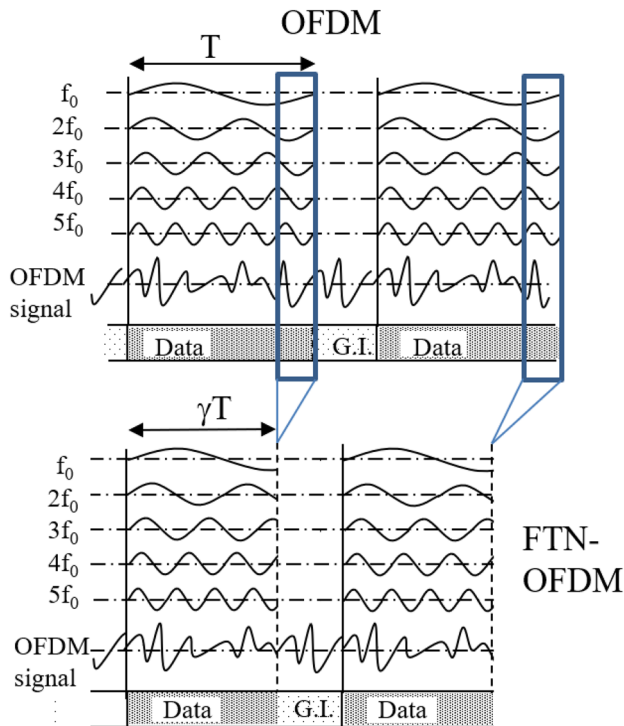

Fig. 5 The concept of FTN. Faster transfer rate can be achieved by truncating the block
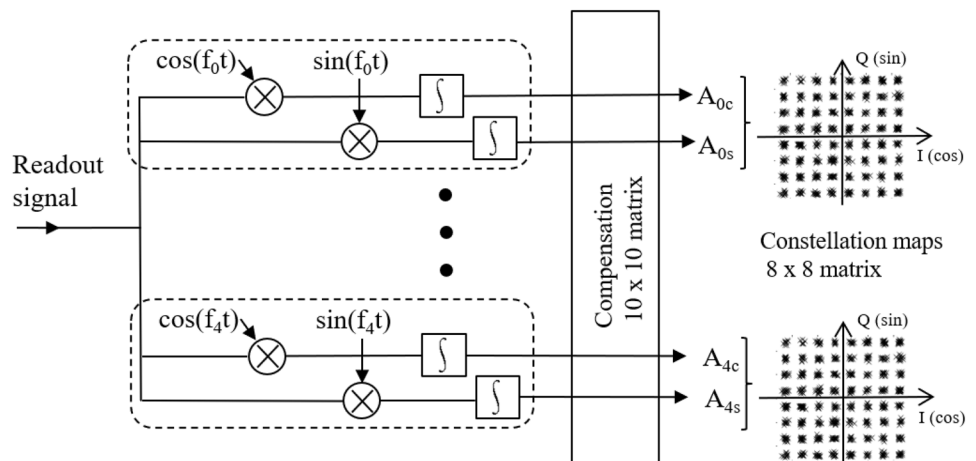
Fig. 3. The advantage of the OFDM method, compared to the conventional PRML readout, was described in Refs. [16, 17].

As shown in Fig. 3, analog signal recording is required to apply the OFDM method to optical discs systems. One way to realize it may be the use of the delta-sigma modulation that is able to convert the analog signal to a sequential binary data for the conventional optical recording scheme [12].

4 The FTN method

The data transfer rate or the storage density in OFDM method is calculated as the number of bits divided by the block length. So it is possible to increase the storage density by shrinking the block length while keeping the number of bits in a block. Figure 5 shows the concept of FTN. The length of the data area is truncated to γT. In such a case, the sampling rate of the block sequence is faster than the Nyquist (FTN) frequency.

In the demodulation process, the integration range in the form (1) becomes $t = 0$ and γT, where $\gamma < 1$ that breaks the orthogonality. However, it can be corrected because it is the deterministic process.

The non-orthogonality generates interference among the ten amplitudes. It is a linear process then a 10×10 matrix is able to reproduce the correct amplitudes from the demodulated ones. Figure 6 shows the schematic of the demodulation process. The ten amplitudes are obtained by synchronous detection and then the matrix is multiplied to obtain compensated five constellation maps.

5 Simulation conditions

The readout signals were calculated using the optical disc model described in Sect. 2. For comparison, two cases: BDXL™ and the proposed FTN-OFDM systems were

Fig. 6 Schematic of the demodulation process of the OFDM method including the compensation with a 10×10 matrix

simulated. The parameters used for the simulation are listed in Table 1. The recording density in the case of OFDM is originally corresponding to 1.4 times that of the BDXL™.

The sampling clock used in the simulation $t = 56$ nm corresponds to the channel clock of BDXL™. The (1,7)RLL modulation [18] with the code rate of 2/3 results in the linear bit density of 84 nm/bit for BDXL™. In this study, $\log_2(64) = 6$ bits are in a subband of 64-QAM. A block with five subbands includes 30 bits in total. The original length (without FTN) of a block was set to 32t, including 4t for guard interval, which corresponds to the linear bit density of $56 \times 32/30 = 59.7$ nm/bits. As an example of FTN, the data area of 28t is reduced to 26τ. The block size becomes 30τ, that corresponds to the linear bit density of 56.0 nm/bit and the truncation ratio of $\gamma = 0.929$.

To evaluate signal quality, the one- and two-dimensional amplitude jitter (A-jitter) [16] were employed for the evaluation and comparison of the BDXL™ and OFDM signals. The definitions are illustrated in Fig. 7. The A-jitter is defined as the deviation of the signal amplitude normalized by the minimum distance among the adjacent averaged levels for both one- and two-dimensional cases.

The reference level number is indicated as "i" in Fig. 7a and b, where the reference level is determined as the average of the samples. The N_i is the number of samples of each reference level. The measured amplitude deviations at the reference levels are expressed as s^2_i in Fig. 7a, s^2_{ix} and s^2_{iy} in Fig. 7b. The minimum distance between a reference level of number "i" and its adjacent reference levels is indicated as W_i.

6 Simulation results

6.1 Compensation of the signal interference caused by FTN

Figure 8 indicates the simulated constellation maps of the FTN-OFDM readout signal with the conditions listed in Table 1. The 8×8 maps are not clear due to the interference
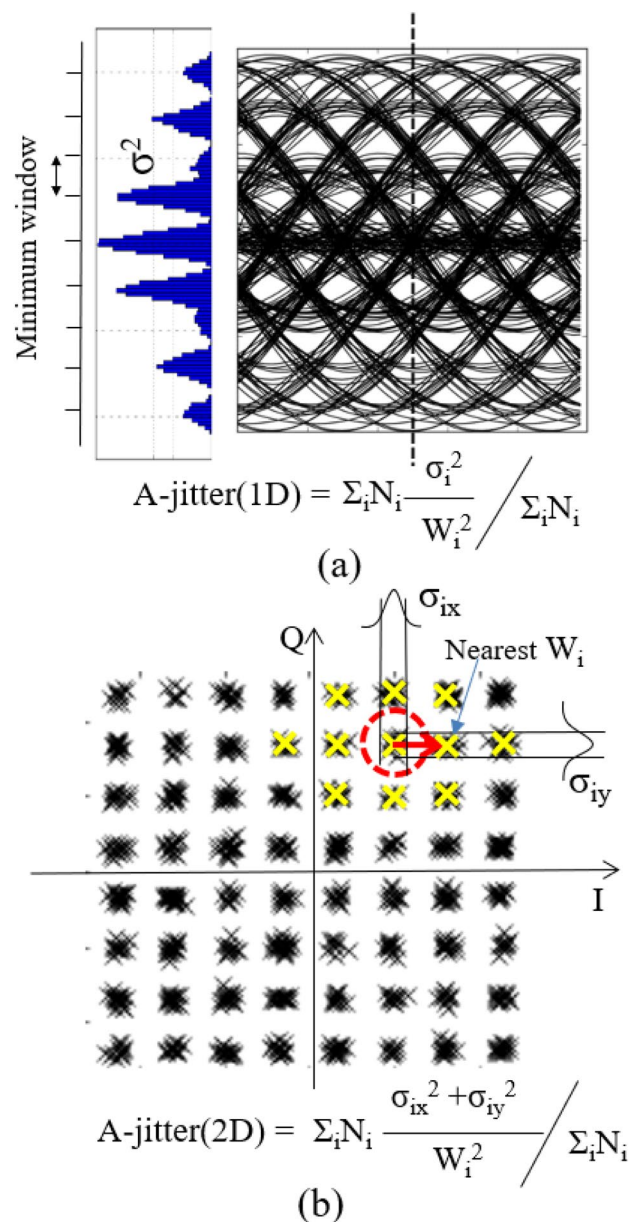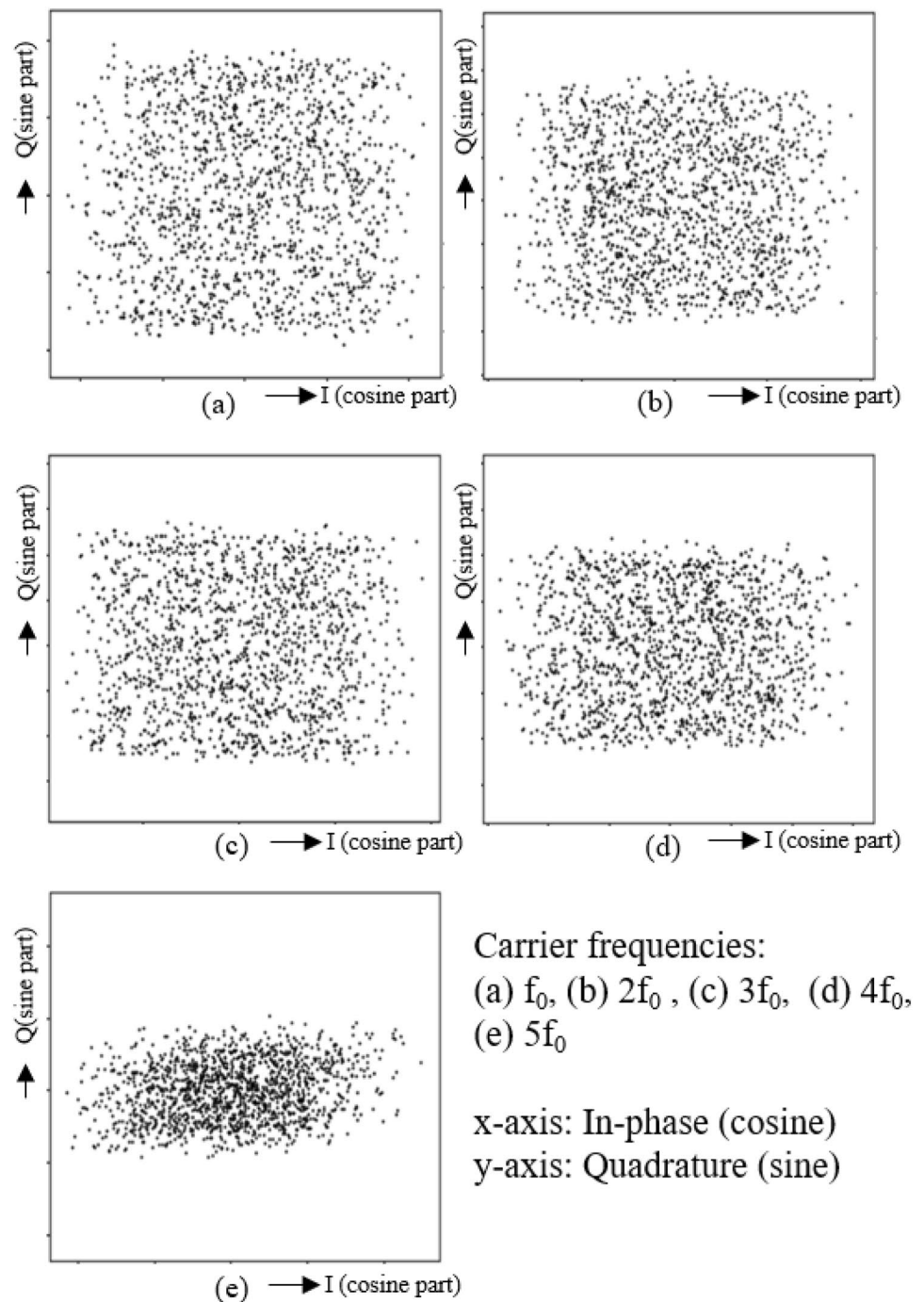
$$A\text{-jitter}(1D) = \Sigma_i N_i \frac{\sigma_i^2}{W_i^2} \Big/ \Sigma_i N_i$$

$$(a)$$

$$A\text{-jitter}(2D) = \Sigma_i N_i \frac{\sigma_{ix}^2 + \sigma_{iy}^2}{W_i^2} \Big/ \Sigma_i N_i$$

$$(b)$$

Fig. 7 The definition of A-jitter. **a** 1-D case of BDXL™. **b** 2-D case of OFDM

Table 1 Parameters of readout optics and modulation codes for the three types of recording signals

	BDXL™	OFDM	FTN-OFDM
Wavelength	405 nm	405 nm	405 nm
NA	0.85	0.85	0.85
Track pitch	320 nm	320 nm	320 nm
Mark width	160 nm	160 nm	160 nm
Mark type	Bitwise	Grayscale	Grayscale
Modulation/coding	(1,7)RLL,PR(12221)	OFDM,5ch,64-QAM	OFDM,5ch,64-QAM
Recording density	84.0 nm/bits	59.7 nm/bits	56.0 nm/bits
Block length (guard interval 4t)	–	32τ	28τ

Fig. 8 Calculated constellation maps of FTN-OFDM method

Carrier frequencies:
(a) f_0, (b) $2f_0$, (c) $3f_0$, (d) $4f_0$, (e) $5f_0$
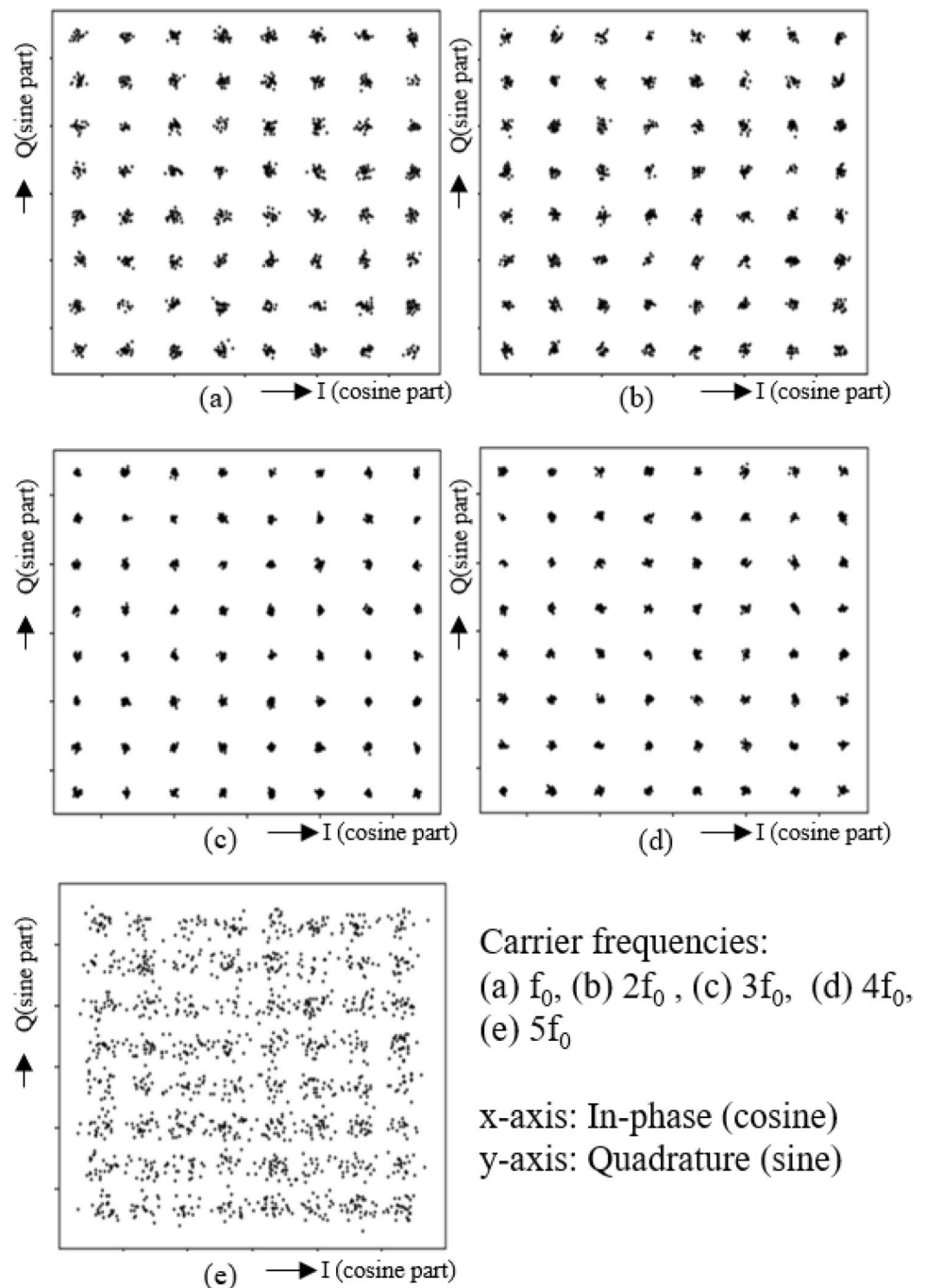
x-axis: In-phase (cosine)
y-axis: Quadrature (sine)

caused by the nonorthogonality. To compensate for the non-orthogonality, a 10×10 matrix was generated using the least mean square (LMS) method and then applied to the detected amplitudes as indicated in Fig. 6. The LMS method was performed with the simulated ten amplitudes and the ten reference amplitudes calculated from the original bit data sequence. Figure 9 shows the results of the compensated constellation maps. The calculated A-jitter was 9.0% while the original value was greater than 20%. It is clearly shown that the proposed compensation method works well.

6.2 Readout signal tolerances of FTN-OFDM method

The resistance of the proposed method to the disturbances encountered in optical disc systems were investigated. The disturbances are implemented as the defocus and the third order aberrations on the pupil function of the optics for readout. A quadratic function of the optical phase is attached to the pupil function for defocus. A phase function of coma aberration is appended on the pupil for disc

Fig. 9 Compensated constellation maps of FTN-OFDM by a 10×10 matrix

Carrier frequencies:
(a) f_0, (b) $2f_0$, (c) $3f_0$, (d) $4f_0$,
(e) $5f_0$

x-axis: In-phase (cosine)
y-axis: Quadrature (sine)

skew. The calculated tolerances of the proposed system and BDXL™ case for comparison are shown in Figs. 10, 11 and 12. In the figures, the horizontal axes have the unit of root mean square (RMS) wavelength of the aberrations. In this study, a defocus of 405 nm and a disc skew of 1.0° correspond to 0.10 rms and 0.052 rms, respectively. Those are determined by the optical parameters of the wavelength, the NA and the cover layer thickness of 0.1 mm with the refractive index of 1.55.

In both BDXL™ and FTN-OFDM calculation, a 21-tap adaptive equalizer is once applied to the readout signal without aberration. The derived coefficients are then used in the other calculation conditions. Two cases of with and w/o FTN are indicated in the figure of the OFDM calculation for comparison. For the FTN-OFDM signal evaluation, the 10×10 matrix was obtained by training with the calculated constellation map and the ideal values. After that, it was applied to the detected amplitudes.
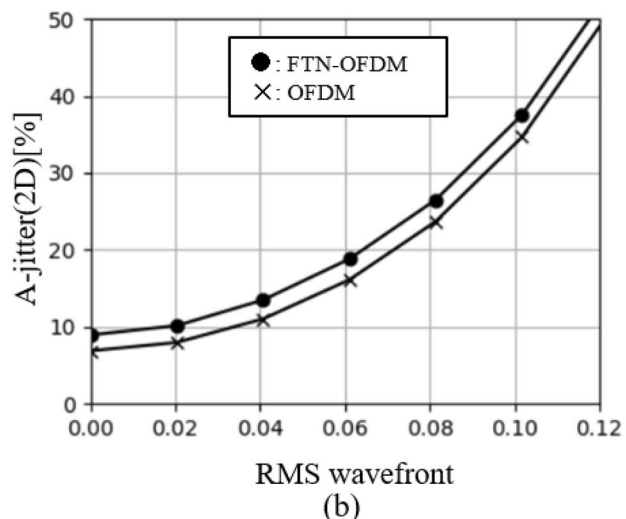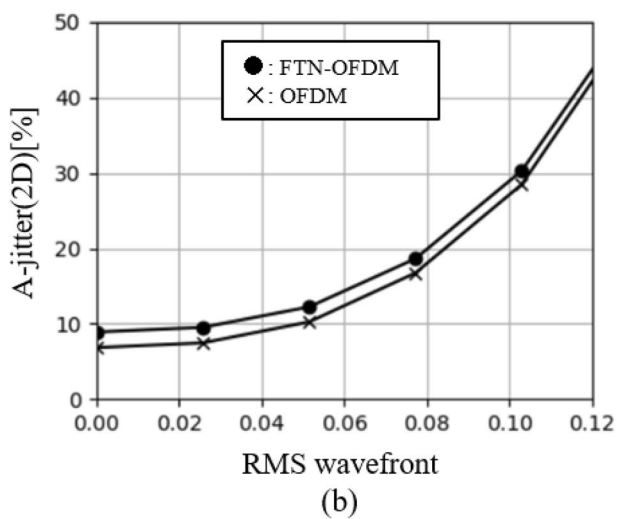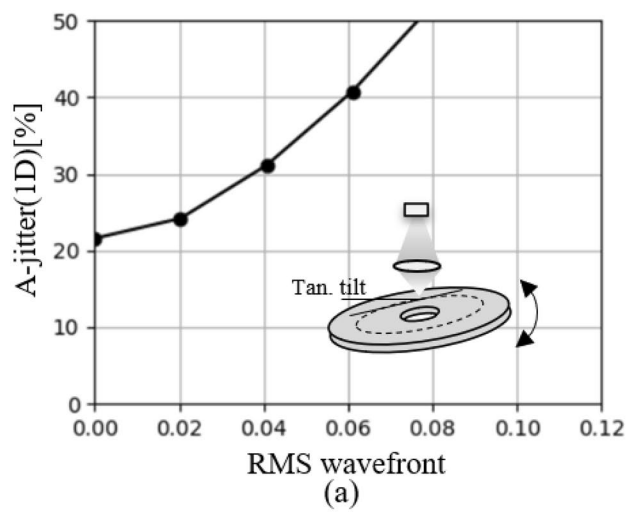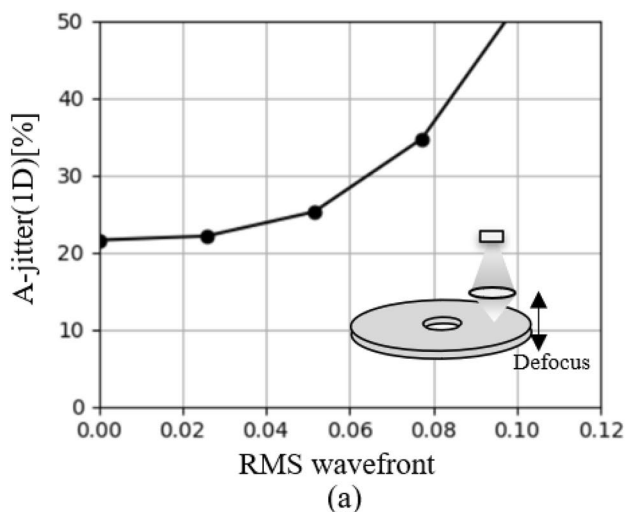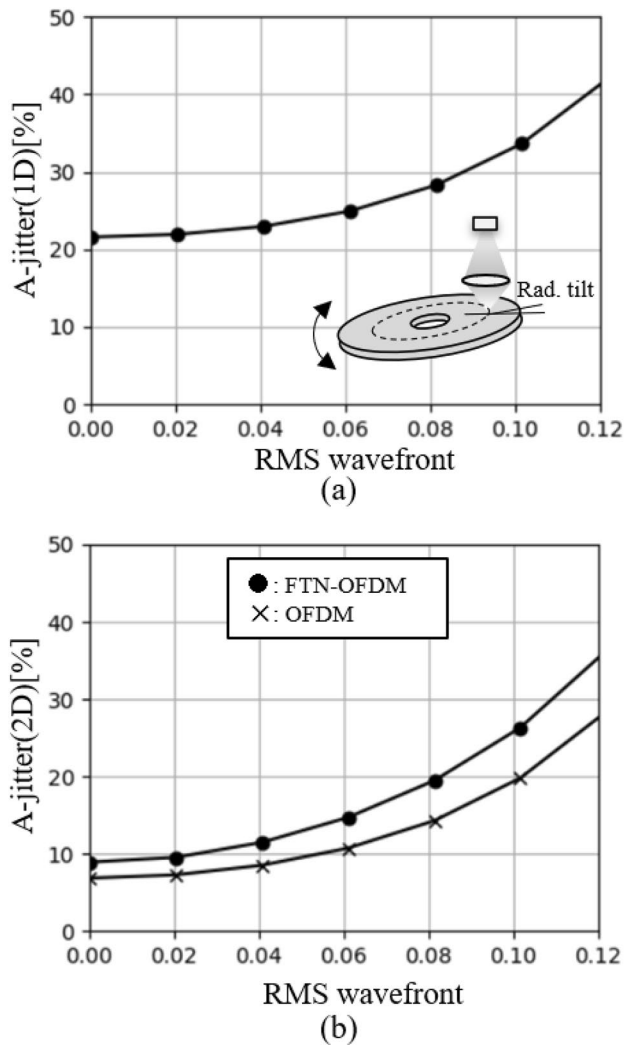
Fig. 10 Calculated defocus tolerances. **a** BDXL™ case. **b** OFDM cases

Fig. 11 Calculated tangential disc skew tolerances. **a** BDXL™ case. **b** OFDM cases

There are some practical indices for evaluating the optical disc signal such as the sequenced amplitude margin (SAM) and the maximum-likelihood sequence error (MLSE) [19]. However I used A-jitter in order to compare the different modulation schemes of the conventional BDXL™ and the OFDM systems. The calculated results of defocus case are shown in Fig. 10a and b. The A-jitter's increase by defocus in the three cases. The bottom value of the A-jitter's in OFDM cases are better than BDXL™ case. It means that a higher recording density can be achieved by the OFDM and more by the FTN-OFDM methods holding a similar tolerance for defocus. The jitter in OFDM case should be spread in two dimensional distribution. So the bottom jitter of OFDM is thought to be smaller than that of BDXL™.

The calculated results of the tangential disc skew case are indicated in Fig. 9a and b. The A-jitter's increase by wavefront aberration as well as the defocus case. It should be noted that the degradation in the tangential disc skew case was found to be mainly caused by signal distortion from the deformation of the LSF of the main track, which is described in Ref. [9].

The results of the radial disc skew case are shown in Fig. 10a and b. Although the tendency is the same as the other cases, A-jitter increases worse in the FTN-OFDM than the original OFDM case as shown in Fig. 10b. Unlike the tangential skew case, the crosstalk from the adjacent track is considered to be dominant in the radial skew case. Then the 10×10 matrix does not work well in this case because the matrix is able to cancel the interference among the subband

Fig. 12 Calculated radial disc shew tolerances. **a** BDXL™ case. **b** OFDM cases

signals caused by the disturbance on the optical readout characteristics but not the noise from the adjacent tracks.

7 Conclusions

To achieve a higher storage density of optical disc systems using OFDM method, an application of FTN method is proposed. The optical disc readout model with considering crosstalk from the adjacent tracks and disturbances of defocus and tangential/radial disc skew realized the estimation of the gain of the recording density for the proposed method. The signal processing of the orthogonality compensation for FTN-OFDM using the 10×10 matrix for 64-QAM and

the 21-tap adaptive equalizer were implemented and combined with the optical disc readout simulation. The simulation results show that the proposed method with a 56 nm/bit recording density provides similar characteristics of system tolerance to the conventional method of BDXL™ with a 84 nm/bit density. It realizes a possibility of 1.5 times recording density of conventional systems.

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