White paper
Blu-ray Disc Format

1.A Physical Format
Specifications for BD-RE

August 2004

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2. Physical Format

The subsequent paragraphs describe the basic philosophy for the physical format of the Blu-ray Disc system, the method for determining principal specification values, and the specific technologies used.

2.1. Basic Parameters

The Blu-ray Disc system has the following three basic parameters:
Laser wavelength: 405 nm
Objective-lens numerical aperture (NA): 0.85
Cover thickness: 0.1 mm

In developing a next-generation optical disc system beyond the CD and DVD systems, researchers put the highest importance to the recording capacity. In principle, the recording capacity of an optical disc is determined by the spot size, which is proportional to the light-source wavelength λ and inversely proportional to the numerical aperture (NA) of objective lens. The capacity, which is in inverse proportion to the square of spot size, can be expressed as follows:

Capacity $\propto$ $(\lambda / NA)^2$

That is, it is possible to increase the recording capacity by decreasing the light-source wavelength and increasing the NA. As the light source of Blu-ray Disc, therefore, we have adopted GaN laser diode (GaN LD) which provides the shortest wave length of all laser diodes, and have set the laser wavelength at 405 nm, taking into account the resistance of plastic material used in the disc. An objective lens has a theoretical upper limit to its NA. Unless near-field light is used, the upper NA limit is somewhere little less than 1.0. It would be practically possible to test-manufacture 0.95-NA objective lens by using two-element lens, which is described later. However, we determined to use 0.85-NA lens, considering the realistic working distance and a production margin. Fig.2.1.1 is a graph showing the relation among wavelength, NA, and capacity. The capacity of DVD with 650 nm wavelength and 0.6 NA can be increased 2.5 times by decreasing the wavelength to 405 nm, and can be doubled by increasing the NA to 0.85. In all, the capacity can be increased five times. That is, Blu-ray Disc (BD) provides an approximately 25 GB recording capacity, compared to 4.7 GB of DVD.

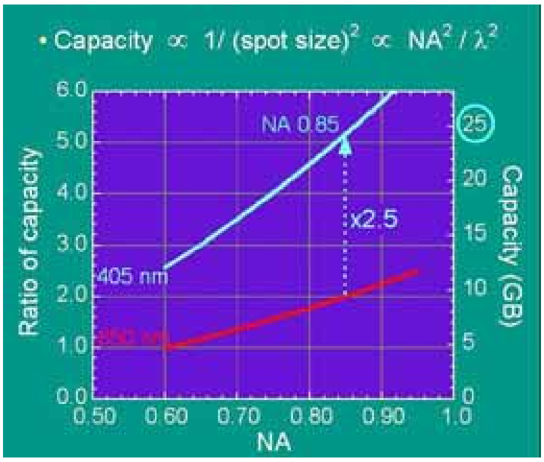


Fig. 2.1.1 Capacity vs. Wavelength and NA

Employing a laser with the shortest possible wavelength and lens with the highest possible NA, as described above, Blu-ray Disc has a sufficiently high recording capacity and long life time, and is expected as a promising next-generation optical disc format.

Optical Tolerances

Decreased laser wavelength and increased lens NA have yielded higher recording capacity. However, the amounts of optical aberrations increase as the trade-off for the increased capacity. In other words, optical tolerances may decrease.

Major optical aberrations that can occur in an optical disc are defocus caused by a residual error or offset of focusing servo, coma aberration caused by a tilt between the optical axis of optical head and the disc, and spherical aberration caused by an error in cover thickness.

The relation of each optical aberration to wavelength λ, NA and cover thickness t can be expressed by the following formulas:

Defocus $\propto \lambda / NA^2$
Coma aberration $\propto \lambda / (t \times NA^3)$
Spherical aberration $\propto \lambda / NA^4$

These are approximate expressions. Actual optical discs tend to have higher optical aberrations, including high-order aberration, relative to NA. Table 2.1.1 shows example results of calculations.

For the specific wavelength, NA, and cover thickness of each of DVD, DVD Blue (hypothetical) and Blu-ray Disc, the table gives the tolerances for tilt, cover-thickness error, and defocus, on the assumption that the amount of aberration is constant.

	Blu-ray	DVD Blue	DVD
Wavelength	405nm	405nm	650nm
NA	0.85	0.65	0.60
Cover thickness	0.1mm	0.6mm	0.6mm
Capacity (proportional)	24.3 GB	14.2 GB	4.7 GB
Tilt	0.64deg.	0.33deg.	0.70deg.
Thickness error	±3.0µm	±13µm	±30µm
	±3.0µm/100µm = ±3.0 %	±13µm/600µm = ±2.2 %	±30µm/600µm = ±5.0 %
Defocus	±0.22µm	±0.42µm	±0.80µm

Table. 2.1.1 Optical tolerances

It is clear from this table that Blu-ray Disc has almost the same tilt tolerance as for DVD, by decreasing the cover thickness to 0.1 mm to compensate for increased coma aberration resulting from decreased laser wavelength and increased lens NA. Even with a shorter-wavelength laser, however, if the cover thickness remained 0.6 mm (as in DVD Blue), the tolerance for tilt would decrease to half that of Blu-ray Disc. In fact, the disc tilt specification for the Blu-ray Disc format is 0.35 degree (almost the same level as for DVD). Therefore, Blu-ray Disc does not require an optical-head tilt compensation servo like the DVD format.

The tolerance for cover-thickness error of Blu-ray Disc is 1/10 that of DVD. However, since the cover thickness itself is 1/6 that of DVD, the thickness-error tolerance of Blu-ray Disc is larger in ratio than that of DVD Blue. A cover 100µm thick can be produced with high precision by sheeting or resin spin-coating, as is described in the following section. Since the Blu-ray Disc format sets the standard value of cover-thickness error in one disc at ±2µm, it does not require a high-speed spherical-aberration compensation servo adaptive to rotation period or high-speed access. On the other hand, the standard value for cover-thickness error between discs is set at ±5 µm, to effectively expand the disc production margin. In addition, this makes it relatively easy to build a low-speed spherical aberration compensation mechanism in the optical head; low-speed compensation for spherical aberration is necessary when a disc is inserted in a drive. This mechanism is indispensable to dual-layer optical discs, in which the layer-to-layer distance is 25µm. Spherical aberration compensation is indispensable to all dual-layer optical discs if they use a shorter-wavelength laser as in Blu-ray Disc and DVD Blue.

The defocus tolerance of Blu-ray Disc is approximately 1/4 that of DVD Blue. The primary cause of defocus is residual focusing-servo error. Considering the performance of recent actuator of fast double-speed DVD drive, it is relatively easy to set the reference servo at the focusing servo's crossover frequency of 3.2 kHz. The standard residual-servo-error value of Blu-ray Disc is 0.045µm, which is approximately 1/4 that of DVD. This value is easily achievable in manufacturing discs. The following section specifies measured data.

2.2 0.1-mm-thick Cover

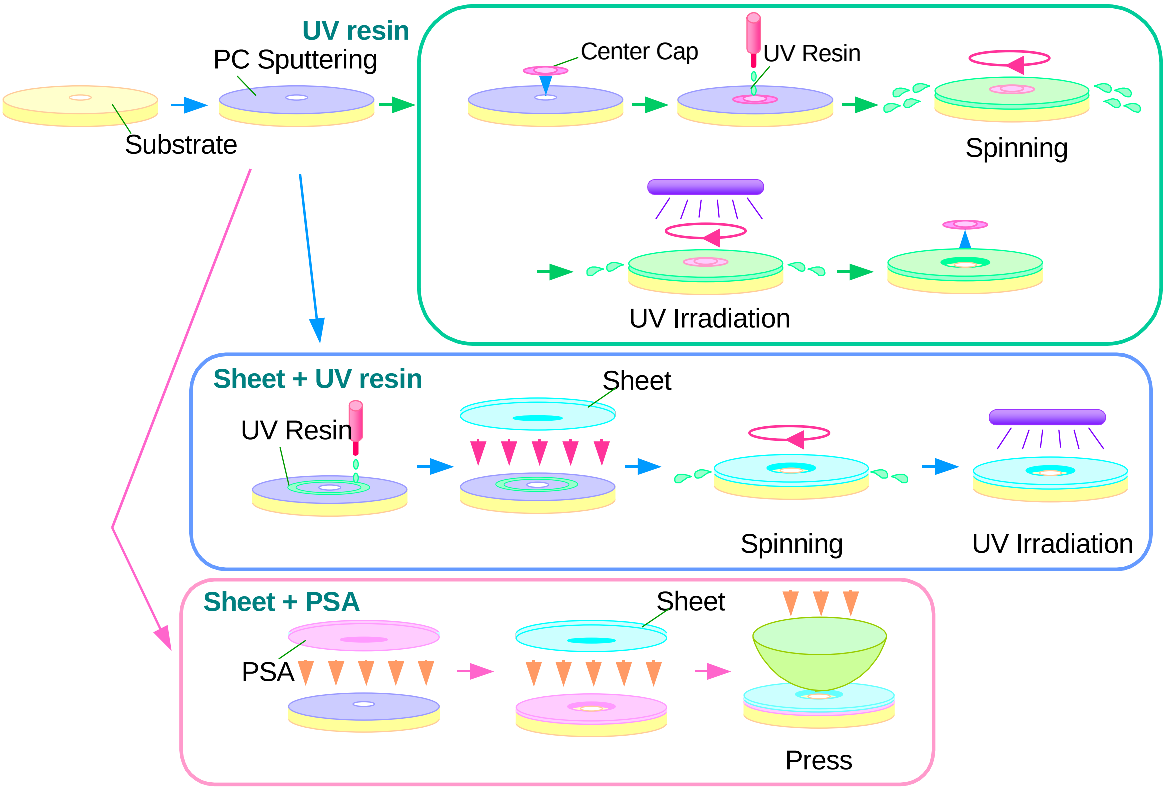
As discussed in the previous section, Blu-ray Disc (BD) employs a higher-NA objective lens and a shorter-wavelength laser to increase the recording density. To enable this, we have set the cover thickness to 0.1 mm, taking account of tilt margin, resistance to damage by dust, and disc production process. Production of a thin cover must meet thickness-related performance requirements, such as median thickness value, and thickness uniformity, as well as optical performance requirements, such as transparency to blue laser beam, and birefringence. In addition, it is also necessary to develop cover-manufacturing process and structure that take account of the residual focus error and disc tilt resulting from combination with a substrate. Table. 2.1.1 gives the cover-related target and standard values for BD are shown as follows;

Thickness variation	<=+/- 2μm
Birefringence	<= 30nm
Disc tilt	<=0.3 deg
Residual focus error	<=45nm
Transparent ratio	>80% (Including surface reflection)

During the early development stage of Blu-ray Disc, two different methods were studied to form a 0.1 mm thick cover of the disc. One is to transfer the pattern to a 0.1-mm-thick base material and then bond a 1.1-mm-thick substrate to the base material. The other is to transfer the pattern to a 1.1-mm-thick substrate by injection molding and then bond a 100μm-thick cover to the substrate. For use in the former method, various pattern-transfer techniques were studied, such as injection molding, and sheet transfer. However, the study revealed that the former method has various problems to be overcome: difficulties in transfer itself and in handling the post-processes, such as lamination of pattern-transferred sheet or base material molded into sheet, formation of layers, and bonding. On the other hand, the latter method, in which a cover is bonded to the 1.1-mm-thick substrate, has two problems. Firstly, the recording layer or reflective layer is formed on the opposite side from that of the conventional optical disc. Secondly, since pits and grooves are to be under the cover, the groove configuration transferred to the substrate cannot be maintained, unlike the conventional disc. However, due to optimization of the groove configuration and development of suitable recording-layer material, cover formation by the latter method has become relatively easy. The Blu-ray Disc cover is mostly produced by the latter method at present.

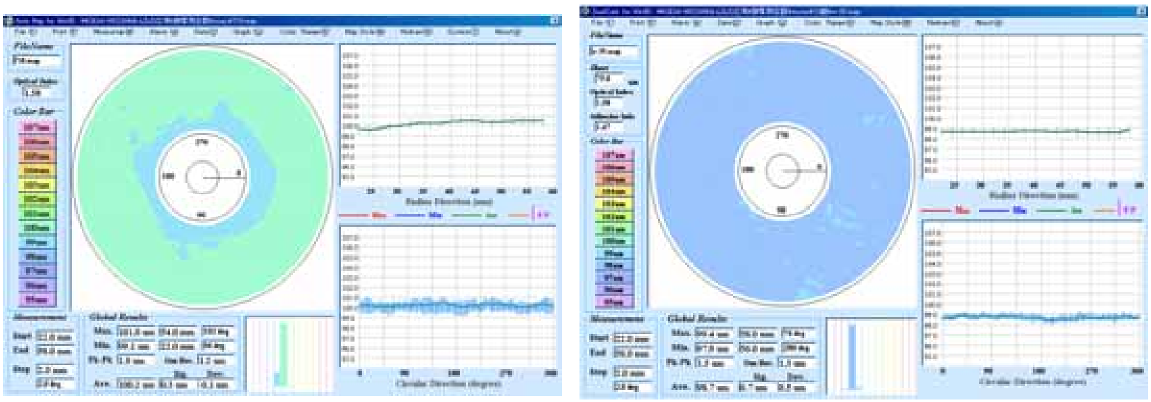
The cover formation techniques can be divided roughly into two groups. One is to form a 100μm thick layer on the substrate using the ultraviolet curing resin (hereinafter referred to as the “UV resin”) employed as the protective layer of CD and as adhesive in DVD. The other is to bond cover sheet to the substrate. Fig. 2.2.1 shows the basic process of each of these techniques: from upper to lower, forming the entire cover using UV resin (Resin Coating Process), bonding cover sheet using UV resin, and bonding cover sheet using pressure sensitive adhesive (PSA). Cover-formation difficulty arises from the thinness of 100μm and the thickness error requirement of within ±2μm. The thickness precision depends on the resin-application precision, manufacturing technique, and the thickness of sheet and adhesive layer.

Fig. 2.2.1 BD cover manufacture process



Resin Coating Process has two problems that must be solved: unevenness of resin thickness on the inner and outer peripheries, and resin upheaval on the outer peripheral area due to surface tension. We have overcome these problems by placing a center cap over the center hole, irradiating resin coat with UV while spinning the substrate, improving the substrate shape, and so on. Since the BD cover is thicker by more than one digit than the protective layer of CD, the resin used for the BD cover requires high viscosity, which also makes the process difficult. This difficulty has been overcome by applying the resin in multiple layers (TDK; the Nikkei Electronics, July 17, 2000 issue). Two techniques have been proposed as the method of bonding cover sheet to the substrate: one using UV resin; the other using PSA. For both techniques, the performance of sheet itself and the method of forming an adhesive layer are of vital importance. When BD was developed in 1996, no materials existed that satisfy the abovementioned stringent performance-related requirements about thickness unevenness, axial run-out (particularly at medium to high frequency range of several hundreds of hertz to several kilohertz), and birefringence. Owing to optical-disc inspection equipment introduced, and repetitive review of the process based on disc evaluation result, the present cover formed by the sheet bonding method meets the required BD specifications. During the early development stage, the sheet bonding method using PSA had problems, such as difficulties in embedding fine groove pattern to achieve high-density recording and in expelling air bubbles, as well as fine axial run-out and poor reliability attributed to uneven PSA coat. However, all these problems have been solved as a result of material development. With this method, it is possible to produce BD cover by applying PSA to a sheet to form a combination structure, and bonding it to the substrate after removing the protective layer. This process is simple. In addition, the cover thus produced is precise in thickness. The sheet bonding method using UV resin is to drip UV resin on the injection-molded substrate with layers formed thereon, spin the substrate to make the resin thickness even, and irradiate the resin layer with UV to cure it. This process is also simple. The UV resin employed as the protective layer of CD and as the adhesive in DVD can be diverted for use in this method, if only its transparency to UV beam and its resistance to corrosion by the recording layer are improved. In addition, since the process resembles the bonding process of DVD, except for substrate thickness, DVD's bonding techniques can be used for this process. The charts of Fig. 2.2.2 show the thickness unevenness of covers formed by the sheet bonding methods using UV resin and PSA, respectively.

Fig. 2.2.2 Cover thickness distribution

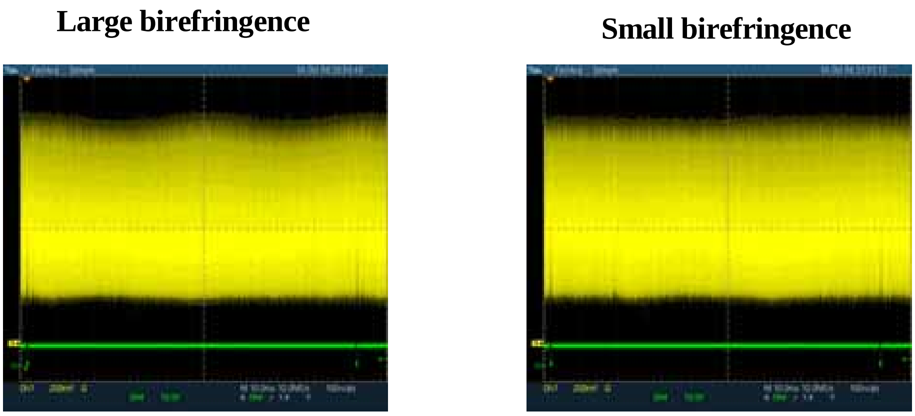


Sheet + UV resin bonding

Sheet + PSA

Birefringence is attributed mostly to the sheet production method, not to UV resin or PSA. Because of high NA, the angle of laser beam converging in the BD cover is large, resulting in the problem of vertical birefringence, as well as the conventional horizontal birefringence. This causes wavefront aberration to occur in the optical system, resulting in poorer imaging performance and fill-condition, that is, deterioration of resolution. Conventionally, birefringence on an optical disc is caused by injection-molding orientation, and can be observed concentrically around the disc center. On a cover sheet, in contrast, birefringence occurs in the sheet-forming direction and in the direction orthogonal to it. On a rotating disc, therefore, birefringence appears in the form of envelope fluctuation (Fig. 2.2.3). It is necessary to reduce birefringence, and envelope fluctuation caused by the birefringence.

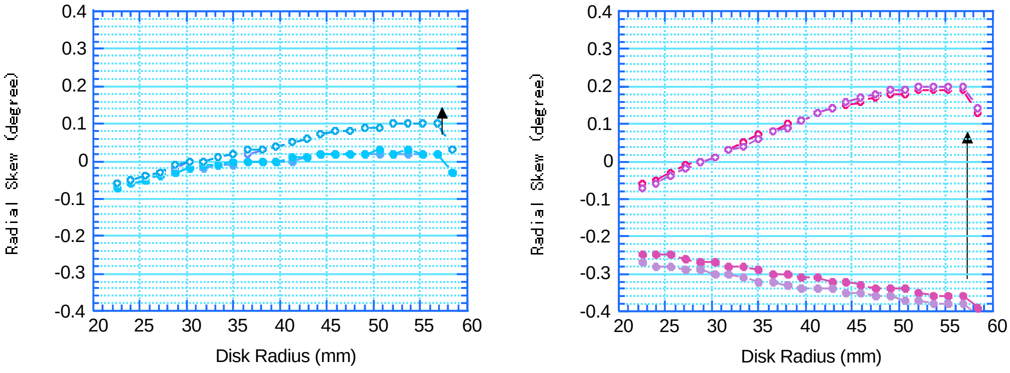
Fig. 2.2.3 RF envelope variation by birefringence


Large birefringence
Small birefringence

Normally, extrusion method or fusion-casting method is used to produce cover sheet. Considering the influence of birefringence and of die-line in the extrusion method, the sheet produced by the fusion-casting method more suitably meets the requirements.

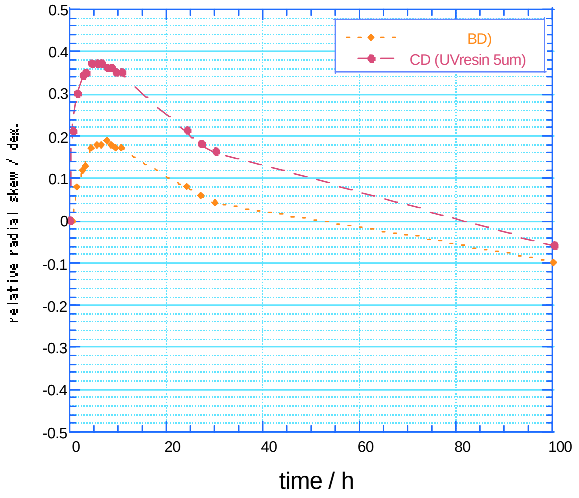
The tilt margin has been increased as the result of decreasing the cover thickness. However, since the BD format assumes a drive concept that does not use a tilt servo, further improvement is necessary in the disc production techniques. Disc tilt has two modes: radial tilt in which the disc is warped radially into a cup shape, and tangential tilt in which the disc is warped in the rotating direction. Radial tilt must be decreased. Disc tilt can also be divided into three types according to the cause: tilt caused by the disc manufacturing process, tilt increasing gradually over time as the disc is aged, and tilt generated by a rapid change in the operating environment. As for the tilt caused by the disc manufacturing process, if the conventional UV resin used as the protective layer of CD were applied as-is to a thickness of 100 μm, the resultant disc would tilt by approximately 1 degree due to curing contraction. To prevent this, it was necessary to reduce the curing contraction characteristic of the UV resin. Generally, tilt increasing with age is evaluated using the acceleration test. However, since there is no known theory regarding disc tilt, like that of recording material deterioration, each manufacturer uses a different acceleration test method. The most common method is to accelerate aging by soaking a disc in the environment at 80°C and 85%RH for some 100 hours, then leave the disc at a room temperature for stabilization, and measure the tilt. The disc tilts as the stress in the substrate, adhesive, cover sheet and/or cover resin is released due to accelerated aging. Fig. 2.2.4 shows the change in tilt as the result of acceleration test. The tilt generated by a rapid change in the operating environment is attributed to the disc asymmetry. Tilt generated by change in temperature involves the influence of linear expansion coefficient and Young’s modulus. Tilt generated by change in humidity involves the influence of imbibition. To decrease this mode of tilt, care must be used when selecting cover sheet and substrate materials and designing the disc structure. Test data shows that the disc tilt of BD caused by environmental change is smaller than that of a single-substrate CD (see Fig. 2.2.5).

Fig. 2.2.4 Aging of disc tilt



Aging Condition:80℃85%RH96Hours

Fig. 2.2.5 Environmental changes of disc tilt



30 degree C, 90%RH, 3days→23 degree C, 50%RH (r = 57mm)

The third and final problem that must be overcome by an optical disc is residual focus error. While the target focus error for DVD is 0.2 µm, that for BD is 0.045 µm, which is nearly 1/4 the value for the DVD. Residual focus error is caused by two factors: one relating to the substrate, and the other relating to the cover. Especially when the sheet bonding method is used to produce the cover, it is important to take heed of the quality of sheet and adhesive. Fig. 2.2.6 shows the residual focus error in each of four optical discs manufactured by different methods.

Fig. 2.2.7 shows the transmittance of cover

Fig. 2.2.6 Residual focus error

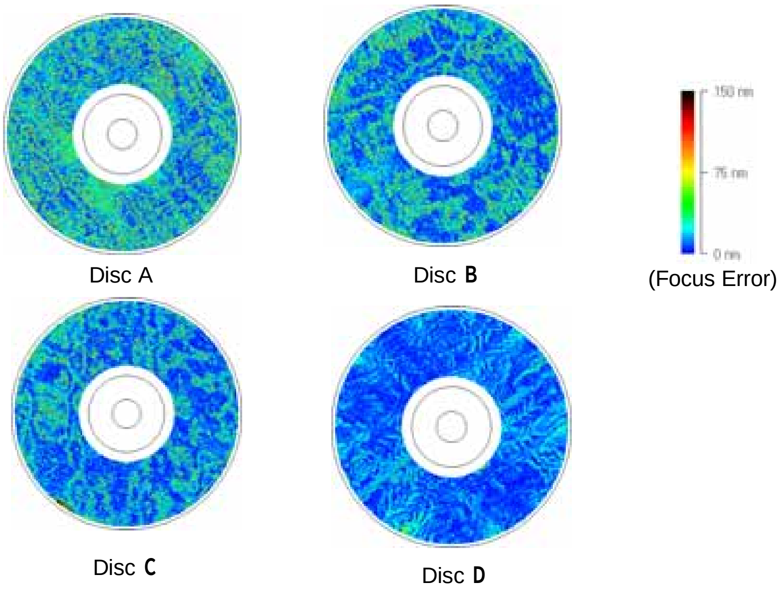
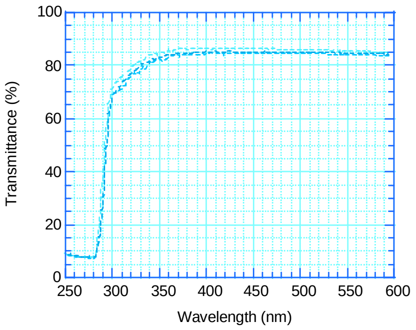


Fig. 2.2.7 Transmittance of cover



2.3 Recording and Playback Technologies

2.3.1 Track Format

The track format of Blu-ray Disc is groove-recording, i.e., recording data only on groove tracks. For the groove recording method, lands are sandwiched between adjacent grooves to block heat transfer between the grooves, preventing signal quality deterioration due to the influence of data recording in adjacent groove tracks with a narrow track pitch. The track pitch between grooves in Blu-ray Disc is 0.32 µm.

2.3.2 Main Blu-ray Disc Parameters

Table 2.3.2.1 shows the main parameters of Blu-ray Disc. As for main optical system parameters, the wavelength of a laser diode is 405 nm, and the NA of objective lens is 0.85. The maximum user data transfer rate is 36 Mbps. The channel modulation is 17PP.

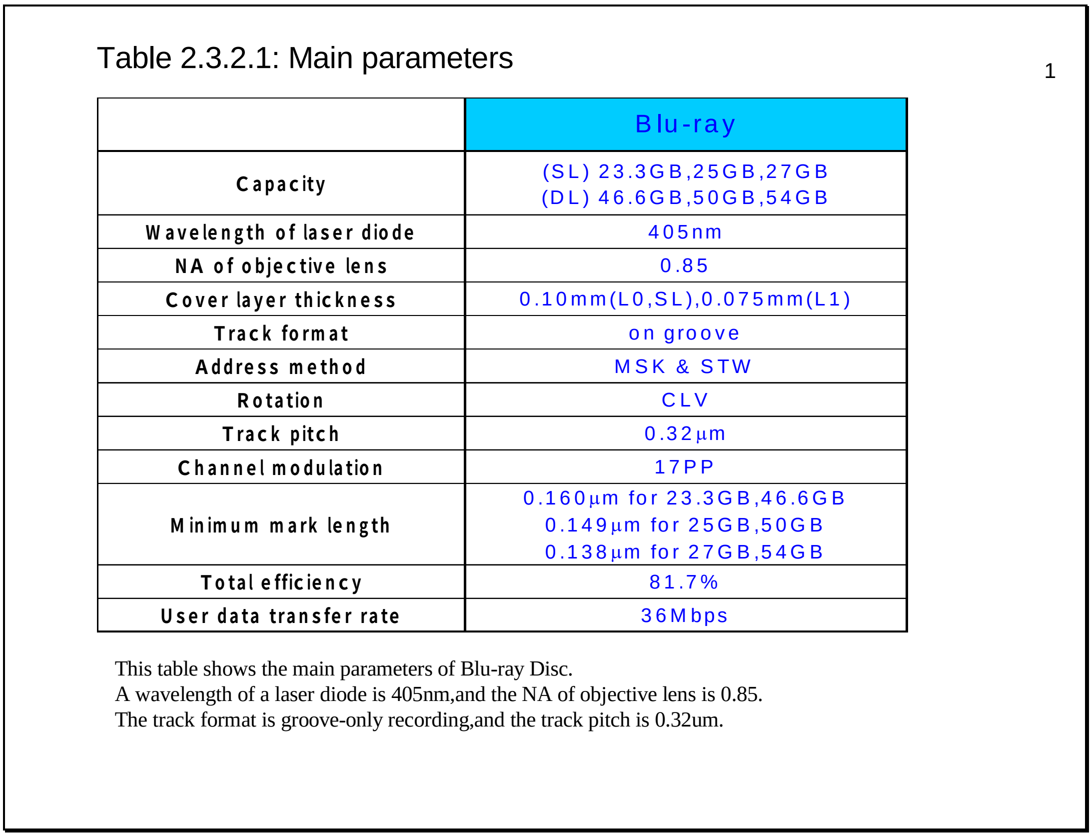


Table 2.3.2.1: Main parameters

1

	Blu-ray
Capacity	(SL) 23.3GB,25GB,27GB (DL) 46.6GB,50GB,54GB
Wavelength of laser diode	405nm
NA of objective lens	0.85
Cover layer thickness	0.10mm(L0,SL),0.075mm(L1)
Track format	on groove
Address method	MSK & STW
Rotation	CLV
Track pitch	0.32µm
Channel modulation	17PP
Minimum mark length	0.160µm for 23.3GB,46.6GB 0.149µm for 25GB,50GB 0.138µm for 27GB,54GB
Total efficiency	81.7%
User data transfer rate	36Mbps

This table shows the main parameters of Blu-ray Disc.
A wavelength of a laser diode is 405nm,and the NA of objective lens is 0.85.
The track format is groove-only recording,and the track pitch is 0.32um.

Blu-ray Disc employs GeSb-based phase-change materials. For a single-layer Blu-ray Disc, the thickness from the disc surface to the recording layer is 100 µm. For a dual-layer Blu-ray Disc, the thickness from the disc surface to the front layer (Layer 1) is 75 µm, and that to the rear layer (Layer 0) is 100 µm. For the dual-layer disc, data recording/playback on the rear layer is performed by laser beam transmitted through the front layer. Therefore, the front layer is required to provide a high and constant optical transmittance of 50% or more, regardless of its state (whether data-recorded or not).

Blu-ray Disc has multiple variations in the recording capacity, to allow user's selection according to use. According to the Specifications Book, the single-layer type has three capacity variations of 23.3, 25 and 27 GB, and the dual-layer type 46.6, 50 and 54 GB. The three capacity variations of each type have been realized by changing the linear recording density, with the track pitch constant. The minimum length (2T) of marks recordable on a disc is 0.160, 0.149 and 0.138µm, in the order of the recording capacity.

2.3.3 Recording and Playback Principles

The recording/playback principle of Blu-ray Disc is described in the following. Fig. 2.3.3.1 shows the configuration of recording/playback block. The NRZI signal encoded according to the 17PP rule is sent to a write pulse compensator where the signal is modulated to multi-pulse. By adjusting the leading edge of the first pulse and the trailing edge of the cooling pulse of the multi-pulse signal, we can control the accumulation amount in accordance with the mark length, enabling the mark edge position precisely. The pulse waveform thus modulated is sent to a laser driver circuit, which modulates the power of laser beam to record mark/space data on a Blu-ray Disc. To play-back recorded data, the reproduced signal through an equalizer is fed to the phase locked loop (PLL). The output signal of the equalizer is also fed to the analog to digital converter (A/D) converted to a digital signal at the clock timing of PLL, then passed through a PRML channel to correct the initial bit error, and output as NRZI signal to the subsequent digital signal processing circuit.

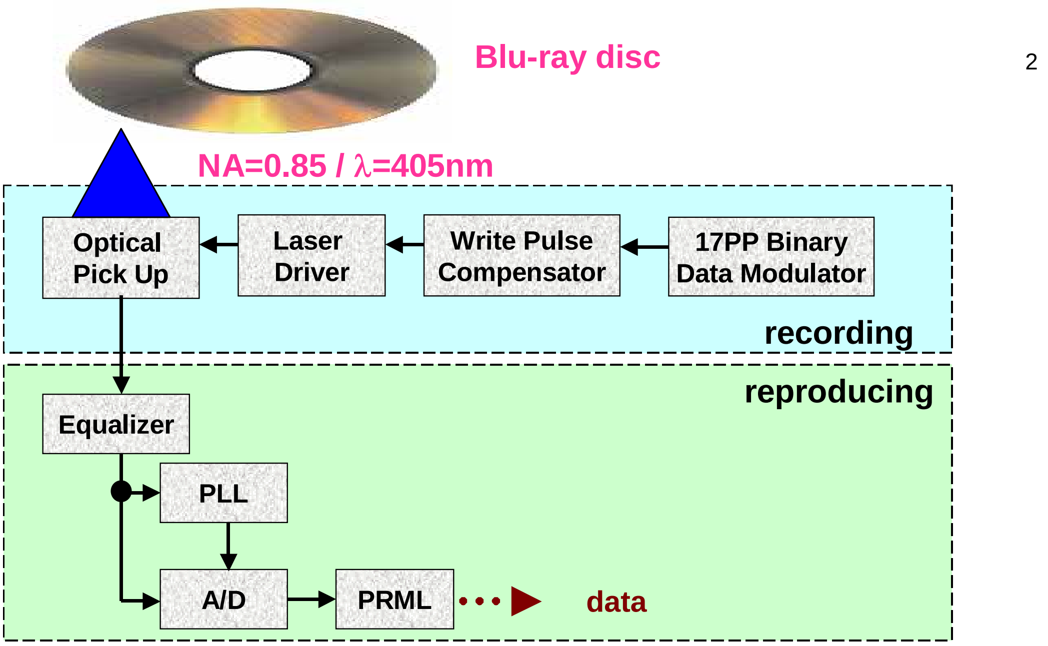


Fig. 2.3.3.1: Block diagram of BD drive

This figure shows a block diagram of Blu-ray Disc drive.
The 17PP modulated binary data is sent to the Write Pulse Compensator to control the mark edge position precisely. The output signal of Write Pulse Compensator goes through Laser Driver and Optical Pick-up. The optical pick-up has a spherical aberration compensator to focus on the both layers of the dual layer disk.
The reproduced signal was equalized and filtered and passed through PRML decoder to correct the initial bit error.

Fig. 2.3.3.1

The mechanism of forming marks on a phase-change media is described below. As the Blu-ray Disc is irradiated with a train of modulated optical pulses of 2T, 3T and 4T as shown in Fig. 2.3.3.2, the recording marks corresponding to the respective code lengths are formed on the disc. Typically, amorphous marks are formed in and around high laser power regions. Marks are erased to become spaces (crystalline) by the erase power irradiation. On the optical disc of phase-change material, laser beam reads difference in physical characteristic (reflectivity) between the thus formed marks and spaces, thereby producing binary data in accordance with to the reflectivity level.

3

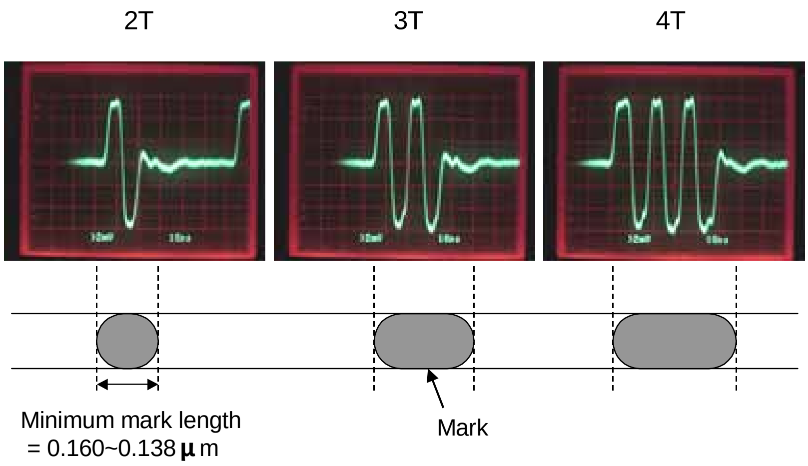


Fig. 2.3.3.2: Write pulse waveform

Fig. 2.3.3.2

2.3.4 Write Strategy

Fig. 2.3.4.1 schematically shows the write strategy for Blu-ray Disc, which comprises pulse-modulated recording waveforms with three power levels of P_W, P_E and P_{BW}. T_{top} denotes the width of the first write pulses, dT_{top} the shift of the leading edge of the first write pulse, T_{MP} the width of all following write, and dT_E the shift of the trailing end of cooling pulse. (For the detail of dT_{top} and dT_E, see the following section.)

4

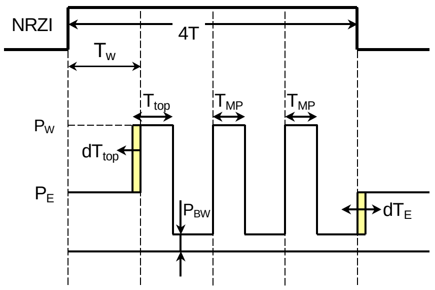


Fig. 2.3.4.1: Write strategy

This figure shows the general write pulse waveform.
This is an example of the write pulse waveform of 4T mark.
Laser power is modulated at three levels.
To control mark edge position precisely, the leading edge of the first pulse and the ending edge of the cooling pulse are shifted by 1nsec resolution.

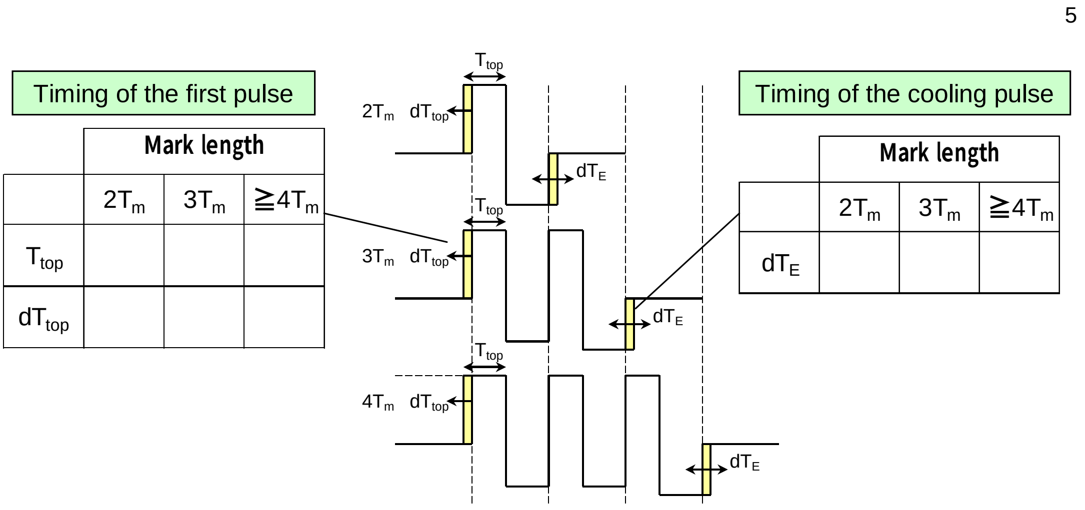
Fig. 2.3.4.1

In accordance with the characteristics and recording capacity of each recording media, the media manufacturer determines the above write-pulse parameters in advance, and embedded in the embossed pit area of each disc.

2.3.5 Adaptive Mark Compensation

This section describes the adaptive mark compensation of Blu-ray Disc. In high-density optical recording, intersymbol interference occurs in which mark edges shift according to the recording condition. To prevent write-signal deterioration resulting from the intersymbol interference, the Blu-ray Disc format is capable of the adaptive mark compensation.

The adaptive mark compensation is to adjust the laser irradiation start point and pulse width, for each of 2T mark ($2T_m$), 3T mark ($3T_m$), and 4T or longer mark ($\geqq 4T_m$), as shown in Fig. 2.3.5.1.



Timing of the first pulse

	Mark length		
	$2T_m$	$3T_m$	$\geqq 4T_m$
T_{top}			
dT_{top}			

Timing of the cooling pulse

	Mark length		
	$2T_m$	$3T_m$	$\geqq 4T_m$
dT_E			

Fig. 2.3.5.1: Adaptive write control

To control the mark edge position precisely, the timing of the first pulse and the timing of the cooling pulse are shifted. The adaptive mark compensation is to adjust the laser irradiation start point and pulse width, for each of 2T mark ($2T_m$), 3T mark ($3T_m$), and 4T or longer mark ($\geqq 4T_m$)

Fig. 2.3.5.1

The leading edge of each recorded mark is adjusted by controlling dT_{top} and T_{top}, and the trailing edge by adjusting dT_E, in accordance with the code length of the mark, to minimize the leading and trailing edge shifts, thereby obtaining high-quality signals.

2.3.6 Signal Processing Technology PRML

Since the Blu-ray format employs a 17PP modulation, the minimum-length mark (2T) is shorter than the optical spot size, resulting in high density recording. When recorded signals are played back, therefore, bit error occurs at a high frequency, especially at the edges relating to minimum marks/spaces. Fig.

2.3.6.1 compares the bit-error distribution between the case where the conventional level-slicing method is used for the signal processing (ECC correction is not performed) and the case where the Partial Response Maximum Likelihood (PRML) method is used. The number of bit errors is indicated for each code-length of mark/space adjacent to each edge of playback signal processed by binarization.

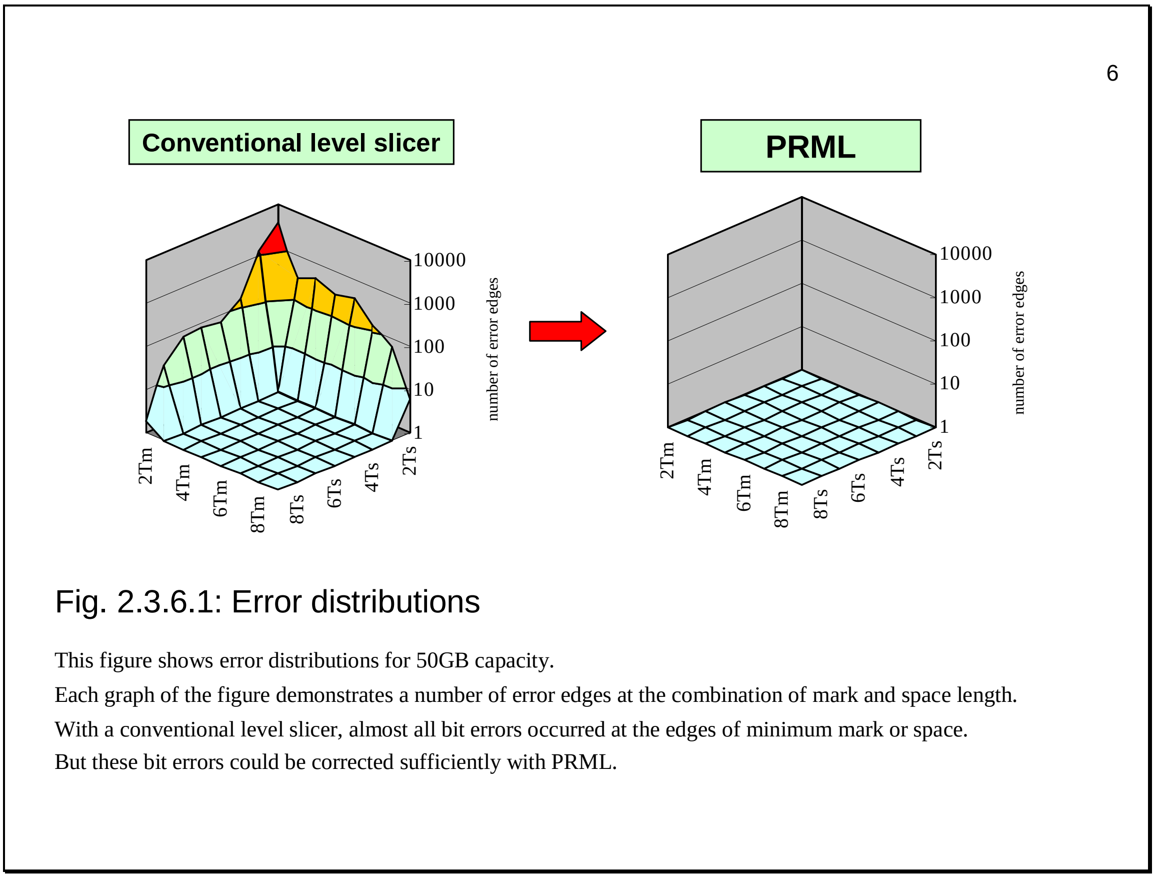


Fig. 2.3.6.1: Error distributions

This figure shows error distributions for 50GB capacity.
Each graph of the figure demonstrates a number of error edges at the combination of mark and space length.
With a conventional level slicer, almost all bit errors occurred at the edges of minimum mark or space.
But these bit errors could be corrected sufficiently with PRML.

Fig. 2.3.6.1

In the case where signals are processed by the conventional method, bit errors are concentrated at the edges relating to 2T marks ($2T_m$) or 2T spaces ($2T_s$). In the case where the PRML technology is used, the number of bit errors has effectively been reduced. The PRML is a signal processing technology suitable for reproducing a high-density recording data.

Signals recorded on an optical disc deteriorate remarkably in the modulation transfer function (MTF). When such recorded signals are played back, the SNR (signal to noise ratio) of minimum code length (2T) in the playback signals decreases, resulting in frequent bit errors at the edges adjacent to 2T. Close study of the error edges adjacent to 2T has revealed that most of such errors occur at the edges adjacent to shorter code length (1T), due to optical intersymbol interference. The PRML carries out Viterbi decoding in advance following 17PP modulation rule. Since 1T code is an inhibition code, error correction to a 2T code is easy.

The PRML technology can reproduce high-quality signals from an optical disc with high linear recording density of up to 27 GB.

2.3.7 Stress Margin

Fig. 2.3.7.1 shows the tangential tilt margin characteristic and radial margin characteristic of a dual-layer Blu-ray Disc on which data is actually recorded using the adaptive mark compensation and read out with PRML technology. The recording capacity is 50 GB. Both layers provide satisfactory bit error rate and tangential and radial tilt margin. The tilt margin of front layer (Layer 1) is wider than that of rear layer (Layer 0), due to thinner front-layer substrate and therefore less influence of spherical aberration.

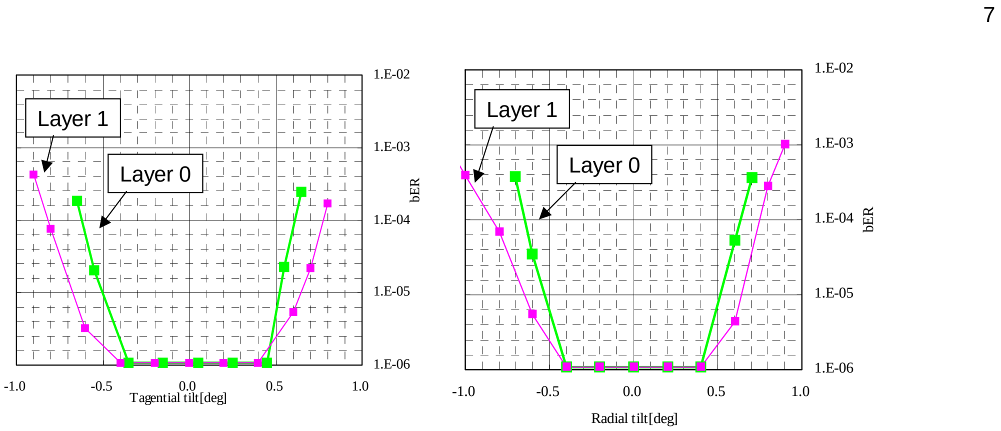


Fig. 2.3.7.1: Dependences of bER on tilt angle

This figure shows the dependences of bER on tilt angle for 50GB capacity.
Left side is radial tilt margin characteristics and right side is tangential tilt margin characteristics.
At every graph, white bots are the results on layer0 and black bots are results on layer1.
With PRML wide tilt margin was obtained in all conditions.
Radial tilt margins reached more than 0.7 degrees and tangential tilt margins attained more than 0.6 degrees.
Tilt margins on layer1 are wider than those on layer0 in both directions.
This results shows an influence of coma-aberration on layer1 is smaller than that on layer0, because the cover layer for layer1 is thinner than that for layer0.

Fig. 2.3.7.1

2.3.8 Limit Equalizer

Generally, a playback signal reading system uses a linear equalizer to improve the S/N ratio around minimum-length pits and to suppress the inter-symbol interference. Disc noise exists mainly in a low-frequency region as shown in Fig. 2.3.8.1. When high frequency around minimum-length pits is selectively boosted using the linear equalizer, the minimum-pit-length signal level can be markedly enhanced with a little increase in the total amount of noise. That is, it is possible to improve the S/N ratio by using the linear equalizer that boosts high frequency. However, since an excessive boosting of high frequency causes an increase in the inter-symbol interference, the conventional linear equalizer has a limit to the S/N improvement.

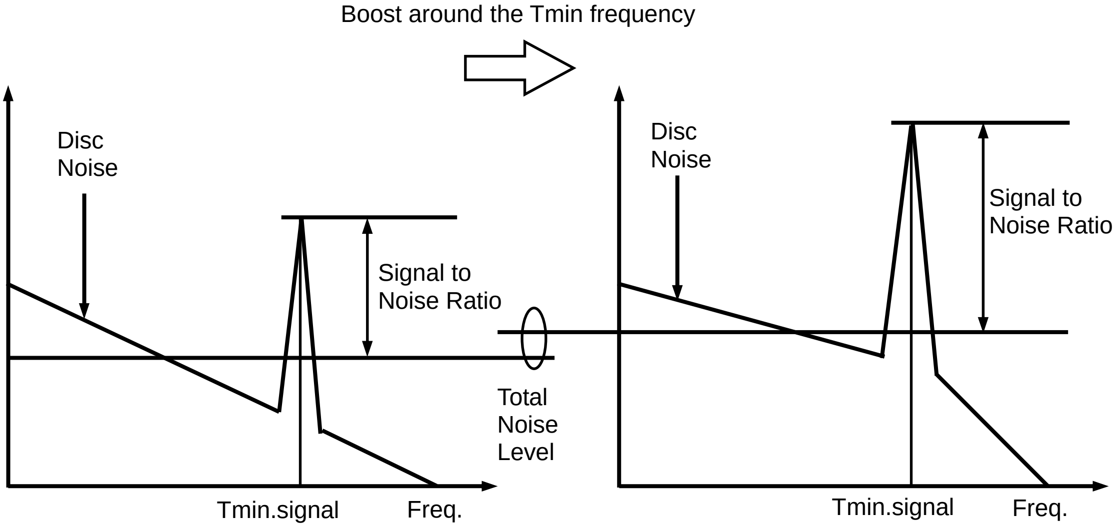


Fig. 2.3.8.1　S / N improvement by the high frequency boost

A limit equalizer is capable of boosting high frequency without increasing the inter-symbol interference. Fig. 2.3.8.2 shows the configuration of the limit equalizer system for use in 17-PP modulation. In this system, a pre-equalizer minimizes the inter-symbol interference at the beginning. The conventional linear equalizer is used as the pre-equalizer. The limit equalizer is located next to the pre-equalizer.

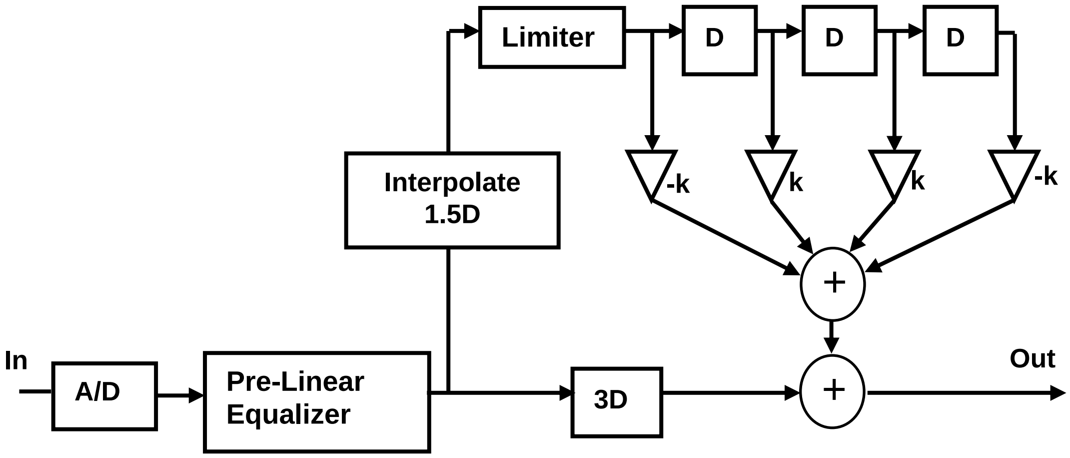
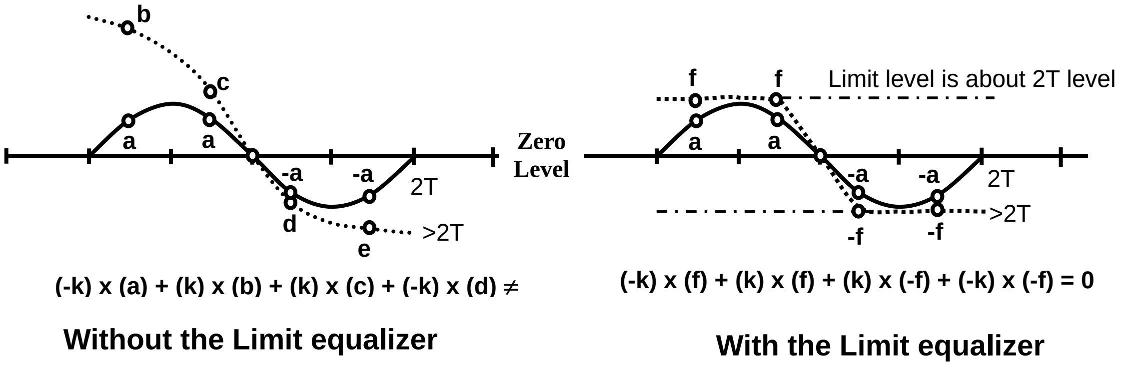


Fig. 2.3.8.2 The configuration of the Limit-EQ

The limit equalizer is almost the same in construction as a finite-impulse-response (FIR) linear equalizer, except that the limiter restricts the amplitude of part of playback signal. The FIR filter acts as a high-frequency-boosting equalizer, and its gain is determined by coefficient “k.” The gain of FIR filter increases with the value of k. Sample values of playback signal are indicated at the small-circle points in Fig. 2.3.8.3.



(-k) x (a) + (k) x (b) + (k) x (c) + (-k) x (d) ≠

Without the Limit equalizer

(-k) x (f) + (k) x (f) + (k) x (-f) + (-k) x (-f) = 0

With the Limit equalizer

Fig.2.3.8.3 Behavior of Linear EQ and Limit-EQ

To understand the operation of the limit equalizer, we pay attention to the zero-cross point and the sample values at points close to the zero-cross point. The operation of the equalizer without a limiter is as follows. Referring to the left-side chart of Fig. 2.3.8.3, if playback signal waveform is symmetrical as indicated by the solid line, the data summed up by the equalizer becomes 0 as expressed by Equation (1), and the zero-cross point does not move.

$(-k)x(-a) + (k)x(-a) + (k)x(a) + (-k)x(a) = 0$ --- (1)

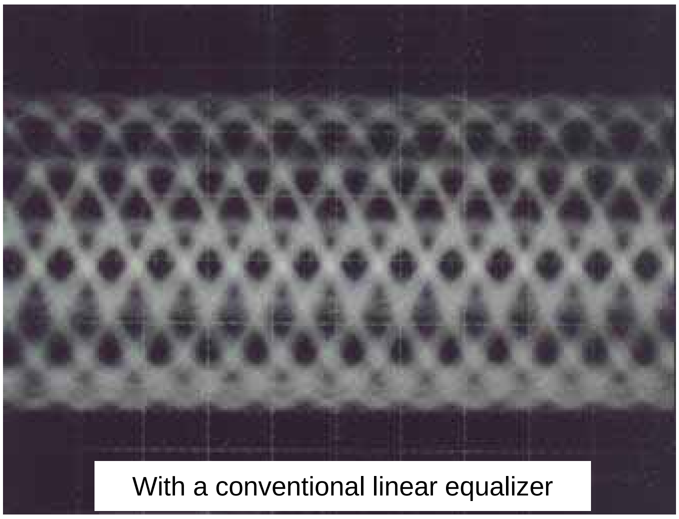
However, if playback signal waveform is asymmetrical as shown in dot line, the data summed up by the equalizer does not become 0 as indicated by Equation (2), resulting in the inter-symbol interference.

$(-k)x(b) + (k)x(c) + (k)x(d) + (-k)x(e) \neq 0$ --- (2)

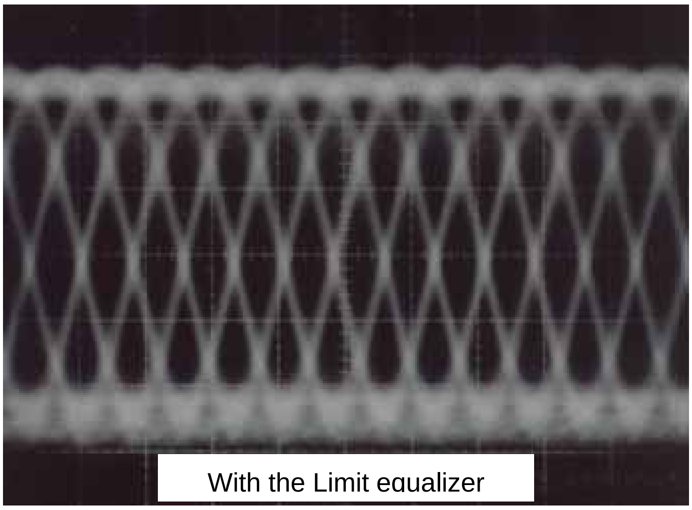
However, if a limiter is used to restrict the signal amplitude to around the peak amplitude level of the shortest wavelength signal, the waveform becomes symmetrical as shown by dot line in the right-side chart of Fig. 2.8.3.3. In that case, the data summed up by the equalizer is constantly 0, as expressed by Equation (3).

$(-k)x(-f) + (k)x(-f) + (k)x(f) + (-k)x(f) = 0$ --- (3)

The limiter does not act on a signal with minimum-length mark, and the equalizer amplifies the signal amplitude. For a low-frequency signal with high amplitude, the limiter restricts the amplitude around the center tap, which is to be added to the sum. The filter gain is effectively decreased. Thus, the limit equalizer can boost high frequency without increasing the inter-symbol interference, and we can improve the S/N. Fig. 2.3.8.4 shows the waveform processed by the limit equalizer, in comparison with that processed by the conventional linear equalizer.



With a conventional linear equalizer



With the Limit equalizer

Fig. 2.3.8.4 Eye diagrams after the Linear EQ and the Limit-EQ

Since the Blu-ray Disc standard adopts high-density recording and 17PP modulation, the minimum mark length is shorter than for the conventional optical disc, so that the S/N ratio is low. Viterbi decoding in the disc drive can compensate for the low S/N ratio, to achieve good playback performance. However, since Viterbi-decoding output is the result after 1/0 determination and is poor in sensitivity, it is not suitable for use in evaluating optical discs in general. The jitter of signals processed by a linear equalizer is dominated by the component attributed to the noise of disc itself rather than the component attributed to the quality of recording marks, making it difficult to determine whether or not the recording state is optimal. In this regard, a linear equalizer is not suitable for use in disc evaluation. The Blu-ray Disc system employs a limit equalizer to improve the S/N and to measure jitter for disc evaluation. With the limit equalizer, it is possible to determine the quality of recorded marks with high sensitivity.

2.4 Modulation code and error correction code for BD

2.4.1. Modulation Code

<u>What is a Moduration Code?</u>

Modulation codes are one of the key elements in optical storage systems such as CD, DVD or BD. In a digital storage system (**Fig. 2.4.1.1**), two parts can be distinguished : the transmitting part, including the write-channel in which a user stores data on the disc, and the receiving part, including the read-channel which aims to restore the original information by reading out the data written on the disc.

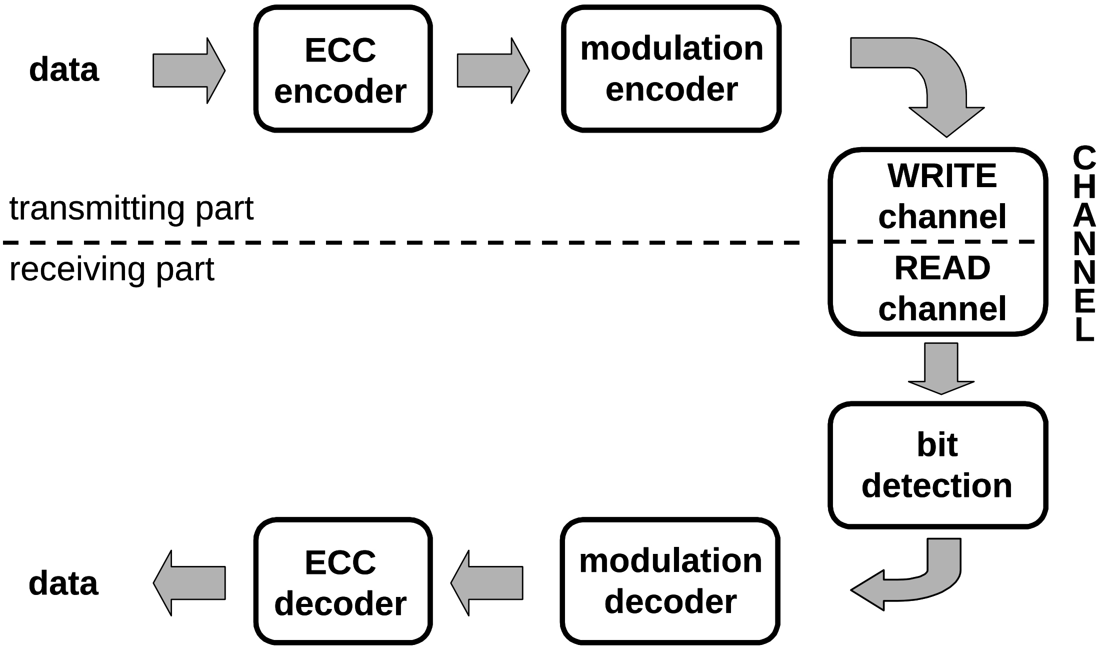


Figure 2.4.1.1: Schematic form of a digital storage system.

In order to realise a sufficiently high level of reliability, the data is first encoded before being stored. This typically comprises an error-correcting code (ECC) and a modulation code (MC). The channel encoder at the transmitting end consists of the ECC-encoder and the MC-encoder. At the receiving end of the channel, there is the physical signal detection with the read head scanning the information on the disc, followed by the bit-detection module, which aims to derive the written bits (also called *channel* bits) from the measured signals as reliably as possible. These blocks precede the channel decoding, which comprises first the MC-decoder, followed by the ECC-decoder.

The ECC adds redundancy in the form of parity symbols, which makes it possible to restore the correct information in the presence of channel imperfections like random errors and/or burst errors that may occur during read-out from the disc. The modulation code serves to transform arbitrary binary sequences into sequences that possess certain “desirable" properties. A very convenient property is that the stored sequences contain neither very short nor very long runs of successive zeros or ones. The reason why this is so originates in how a stored sequence is read from the storage medium.

In optical recording, the modulation of the physical signals is concerned with two physical states of the disc: it is the level of reflectivity (high and low) of the marks (or *pits*) and spaces (or *lands*). One physical state can be associated with channel bit "1", the other with bit "0". This representation is commonly known as NRZI. An equivalent representation of a channel bitstream is the NRZ notation, where a "1"-bit indicates the start of a new mark or space, and a "0"-bit indicates the continuation of a mark or space. An

NRZI channel bitstream can be partitioned into a sequence of *runs*, where each run consists of a number of consecutive channel bits of the same type. The number of bits in a run is called the *runlength*. A small part of two tracks on the disc is shown in **Fig. 2.4.1.2**. Along the track, physical marks and spaces alternate: their lengths are multiples of the channel bit length *T*.

Very short runs lead to small signal amplitudes in the read-out by the physical detection, and are therefore more prone to errors in the bit-detection module. Moreover, very long runs lead to inaccuracies in the *timing recovery*, which is dealt with by a *phase-locked loop* (PLL). The PLL regenerates the internal bit "clock" by adjusting it at each transition. Areas on the disc with too few transitions may cause "clock-drift". Avoiding very short and/or very long runs is achieved by using a *runlength-limited* (RLL) code, which constrains the allowable minimum and maximum runlengths that occur in the channel bitstream. The RLL constraints are described in terms of two parameters, d and k: the minimum and maximum runlengths are equal to d+1 and k+1. For the *uncoded* case, d=0 and $k=\infty$. In NRZ notation, a run of length m+1 is represented by a "1"-bit followed by m "0"-bits. Hence the (d,k)-constraint in NRZ notation requires that the number of "0"-bits between two successive "1"-bits is at least d and at most k. Most RLL codes are constructed in NRZ notation. Subsequent transformation from NRZ to NRZI yields the channel bits that are actually written on the disc: this is done by a so-called 1T-precoder, which is an integrator modulo 2 (Fig. 2.4.1.2). Since the RLL constraints forbid certain specific patterns, it follows that a sequence of source bits must be translated into a longer sequence of channel bits; the ratio of the length of the original and encoded sequences is called the *rate* of the code.

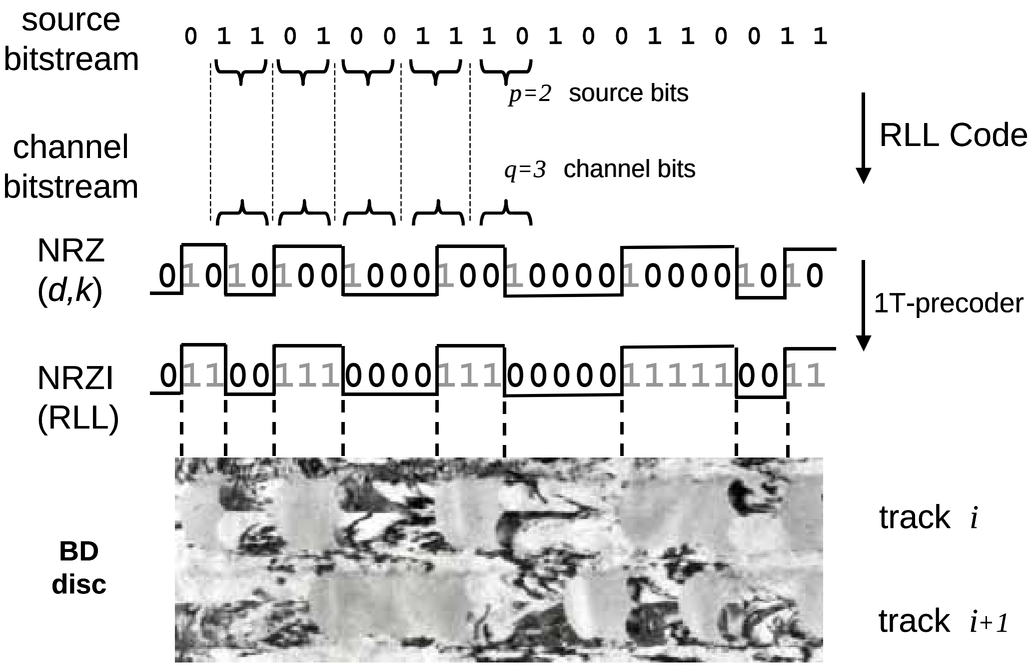


Figure 2.4.1.2: RLL d=1 coding for BD optical recording.

Why d=1 Constraint for BD ?

High-capacity storage applications like BD employ such small bit sizes that the signal waveform generated by the physical detection for a given bit location does not only depend on that single bit, but also on a limited number of neighbouring bits. This bit-smearing effect is better known as *inter-symbol-interference* (ISI). The ISI is characterised by the impulse response of the channel, or, equivalently, by its Fourier transform which is known as the modulation transfer function (MTF) of the channel. The MTF indicates the response of the channel for each frequency in the system.

In optical recording, the MTF has an almost linear roll-off up to the cut-off frequency of the channel (**Fig. 2.4.1.3**).

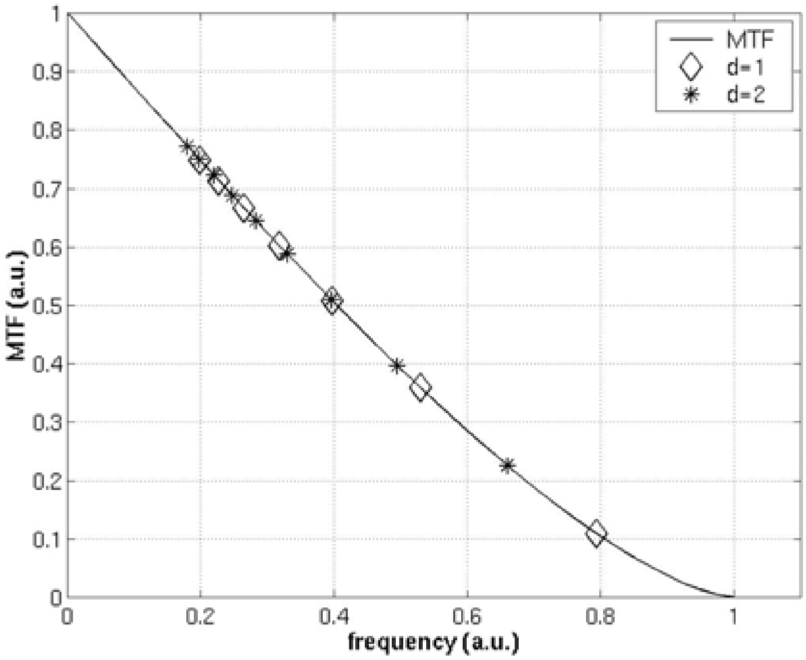


Figure 2.4.1.3: MTF for the optical recording channel as a function of frequency (in arbitrary units, with the cut-off at “1”) with the frequencies of the pure tones ... | nT_d | nT_d | ... superimposed.

Therefore, short runlengths in the channel bitstream, which lead to high-frequent signals, suffer most from ISI and are thus more prone to errors during read-out. One of the purposes of runlength-limited coding is to impose constraints that do not allow these high-frequent bit-sequences. To illustrate this principle, we discuss the effect of employing three different d-constraints, for d=0 (uncoded), d=1, and d=2, while maintaining the same density of *source* bits on the disc. So let T denote the common physical size of a source bit. Using a d-constrained code at a rate R_d, the physical channel bit size T_d will necessarily satisfy $T_d = R_d\, T$. **Fig. 2.4.1.4** shows the respective channel bit lengths and the highest frequency in the system (which correspond to an alternation of runs of minimum runlength). Here, we of course have R_0=1 in the uncoded case. Furthermore, we assume that practical codes are used that have rates R_1=2/3 and R_2=1/2, which are close to the maximal achievable code rates of 0.6942 and 0.5515, respectively. The minimum runlength for d=1 equals $2T_1$=4/3T, which is larger than the minimum runlength T for d=0; also, the minimum runlength for d=2 amounts to $3T_2$ = 3/2T, which is larger than the minimum runlength for d=1. Consequently, the highest frequencies f_d in the system are

$$f_0 = \frac{1}{2T} > f_1 = \frac{1}{4R_1T} = \frac{3}{8T} > f_2 = \frac{1}{6R_2T} = \frac{1}{3T}\,.$$

This relation reveals the increasing low-pass character of the code for increasing d constraint, which is the major attractiveness of RLL coding. This becomes also clear from **Fig. 2.4.1.3**, which shows the MTF with the frequencies of the pure tones ... | nT_d | nT_d | nT_d | ... for n=d+1, d+2, ... superimposed.

However, note that the channel bit length (or *timing window*) decreases for increasing d constraint, which leads to a greater sensitivity with respect to *jitter* or *mark-edge noise* in the system. This counteracting effect favours the use of a *lower d* constraint. The practical choice for the d=1 constraint in BD is the optimal compromise between mark-edge noise (lower d) and ISI (higher d). The k-constraint has been chosen to be k=7, from which the acronym “17PP” has been derived.

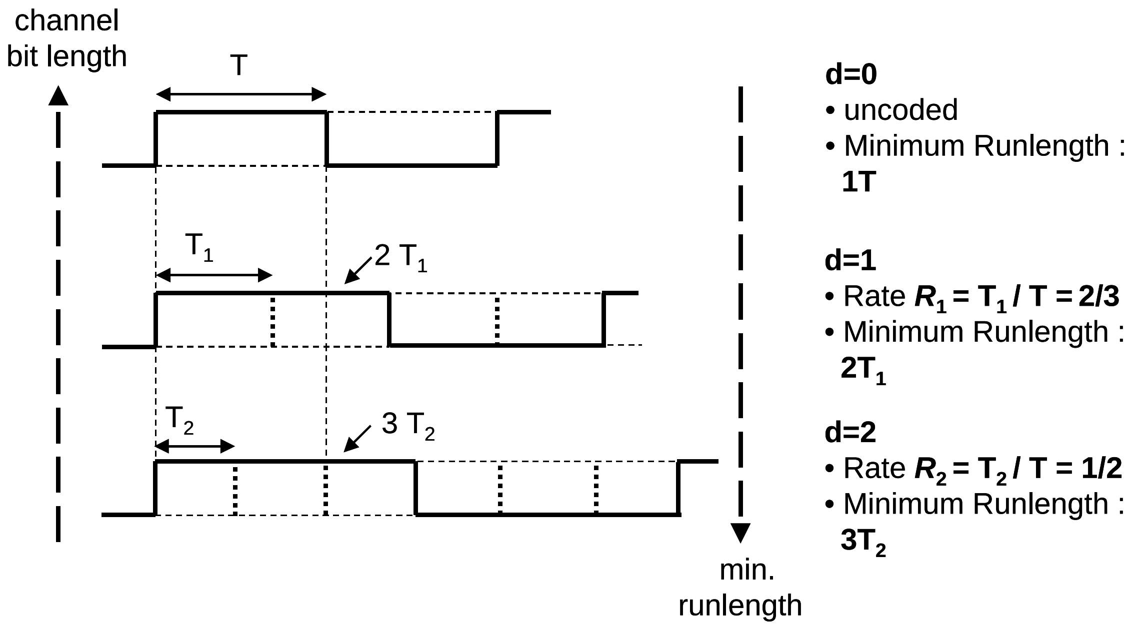


Figure 2.4.1.4 Channel bit length and minimum runlength for different *d* constraints at the same recording capacity.

Why 17PP "Parity-Preserving" Code?

All RLL codes used in optical recording are *DC-free*, that is, they have almost no content at low frequencies. We consider NRZI channel bits b_i with bipolar values ±1. A sequence b_1, b_2, ... is called *DC-free* if its *running digital sum* (RDS; the integral of the bipolar channel bitstream)

$$RDS_i = \sum_{j=-\infty}^{i} b_j$$

takes on only finitely many different values. Then, the power spectral density function vanishes at DC. The DC-free property is needed for a number of reasons: (i) for separation of the data signal from disc noise such as fingerprints or dust, (ii) for control of the slicer level, and (iii) for the servo systems.

We shall now discuss a general method to achieve DC-control in RLL sequences. DC-control is performed via control of the running digital sum (RDS). A very useful concept herein is the *parity*, the number of ones modulo 2, of a sequence of bits. Recall that an NRZ "1"-bit indicates the start of a new run in the (bipolar) NRZI bitstream. Hence, because of the 1T-precoder between NRZ and NRZI channel bitstreams, each "1"-bit in the NRZ bitstream changes the polarity in the corresponding NRZI bitstream. Consequently, an *odd* number of ones in a segment of the NRZ bitstream *reverses* the NRZI polarity after that segment while an *even* number of ones leaves the polarity unchanged.

The above observation can be used for DC-control as follows. Suppose that for a certain segment of the NRZ bitstream, we can choose between two candidate sequences, one with parity "0", the other with parity "1". Then the part of the NRZI bitstream *after* this segment will have a contribution to the RDS where the *sign* depends on which of the two sequences is chosen. The *best* choice is of course the one that keeps the value of the RDS as close to zero as possible. We refer to these segments as *DC-control segments*. In order to realise DC-control, we have to insert DC-control segments at regular positions in the bitstream. Such positions are referred to as *DC-control points*.

A clever and efficient method for DC-control, as used in the 17PP modulation code of BD, is via the use of a *parity-preserving* code (**Fig. 2.4.1.5**). Such a code preserves the parity upon RLL encoding, that is, the parity of a source word is identical to the parity of the corresponding channel word. Single DC-control bits are inserted (at DC-control points) in the *source* bitstream. Changing a DC-control bit from 0 to 1 changes the parity in the source bitstream and hence also in the NRZ channel bitstream: this property enables the selection of the polarity of the NRZI channel bitstream, and thus allows for DC-control. The overhead required for each DC-control point in the 17PP code is exactly equal to one source bit, which amounts to the equivalent of 1.5 channel bits. This makes the 17PP parity-preserving d=1 code 25% more efficient at each DC-control point, compared with conventional methods for DC control.

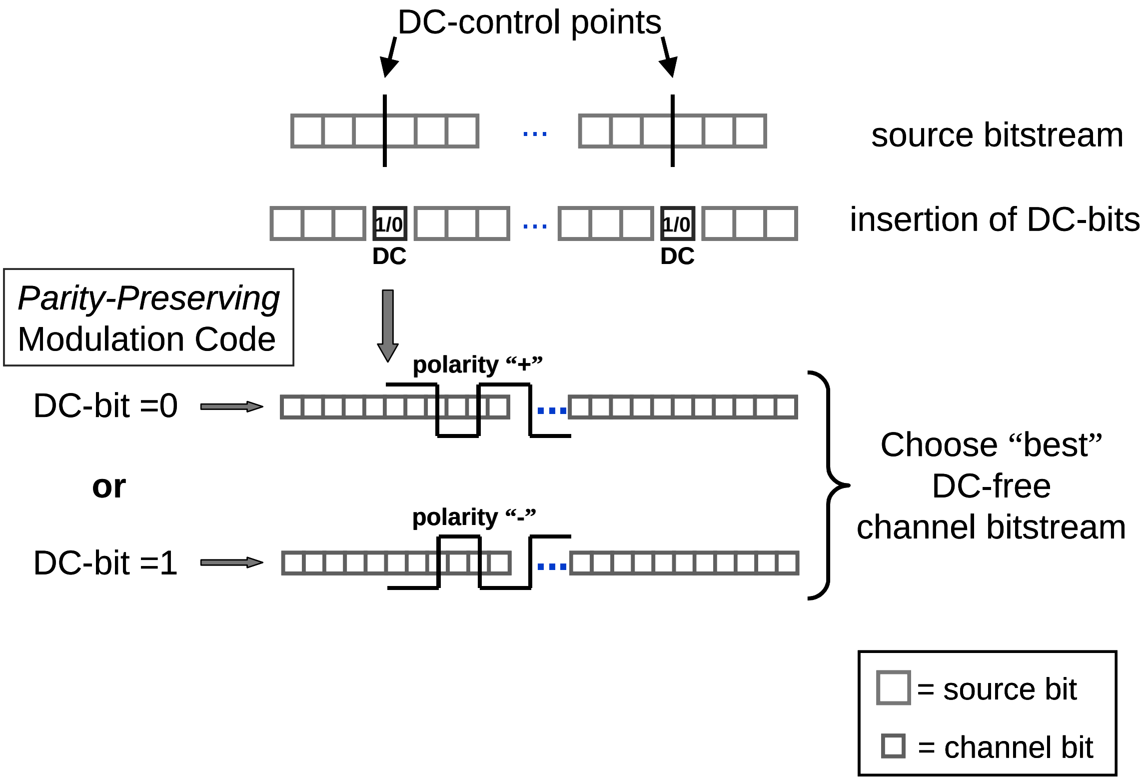


Figure 2.4.1.5: Principle of DC-control via *parity-preserving* modulation code.

The 17PP code has been designed with one additional favourable property in the sense that it prohibits the occurrence of a large number of consecutive minimum runlengths (2T) which is known as the RMTR constraint. The minimum runlengths lead to low signal levels, and by restricting their occurrence, the read-out performance is improved.

2.4.2 Error correction format

In optical recording roughly two types of errors can be distinguished: single or random errors and burst errors. Single errors are caused by noise in combination with other sources of signal deterioration such as tilt of the disc or defocus of the laser spot on the disc. They are called single errors because they only affect one or two bytes. Burst errors are caused by defects on the disc surface like scratches, dust, fingerprints etc.

The error correction system should be adapted to the physical properties of the medium on which the data is stored. Blu-ray Disc is, due to its small spot, the thin cover layer and the high numerical aperture, more sensitive to burst errors than for instance the DVD system. The same defect on a Blu-ray Disc will affect more data bits than on a DVD Disc. The error correction system of Blu-ray Disc should therefore be able to cope very well with long burst errors.

The maximum number of errors that can be corrected depends on the number of parity symbols added. For each two parity symbols added, one error can be corrected. This is assuming that nothing is known beforehand about the error. If the location of an error within the code wordiscnown beforehand, only the erased value of the error has to be calculated. For each parity symbol added, one erased value can be calculated, i.e. one erasure can be corrected. So it is advantageous for the error corrector to use prior knowledge of the error locations in the decoding process. Due to the nature of the errors, this is not possible for random errors, but it is very well possible for burst errors. It requires a burst indicator mechanism that can detect bursts of errors before the correction starts.

Blu-ray Disc uses an error correction system with a very efficient way of burst indication: a picket code. The structure of such a picket code is shown in **Fig.2.4.2.1**. The pickets are columns that are inserted in between columns of the main data at regular intervals. The main data is protected by a Reed Solomon code that is strong and efficient. The pickets are protected by a second, independent and extremely strong Reed Solomon code. When decoding, first the picket columns are corrected. The correction information can be used to estimate the location of possible burst errors in the main data. The symbols at these locations can be flagged as erasure when correcting the code words for the main data. This strategy of applying erasures is shown in **Figure 2.4.2.1**.

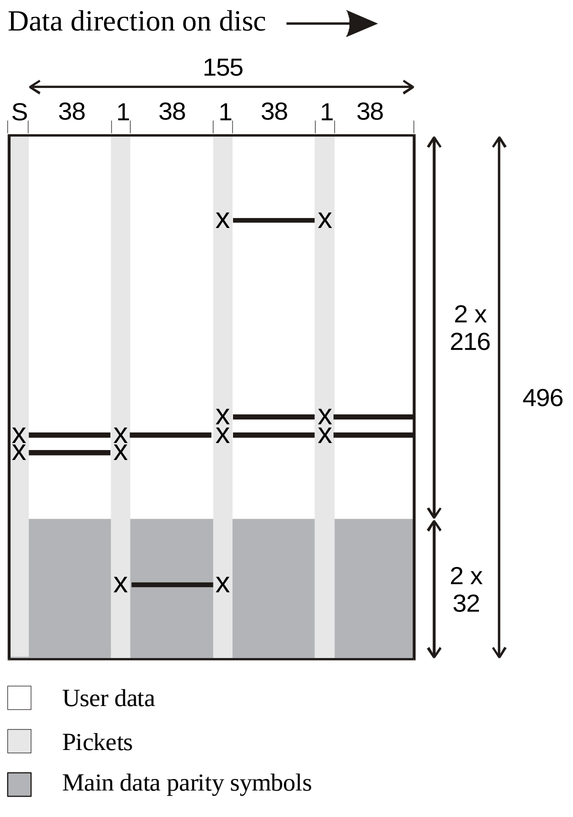


Figure 2.4.2.1 Schematic representation of the Blu-ray Disc picket code

A Blu-ray Disc error correction block (ECC block) can store 64 kilobytes of user data. This data is protected by the so called Long Distance Code (LDC) which has 304 code words with 216 information symbols and 32 parity symbols giving a code word of length 248. These code words are interleaved two by two in the vertical direction such that a block of 152 bytes x 496 bytes is formed as shown in **Fig.2.4.2.1**. A Blu-ray Disc ECC block contains 4 equally spaced picket columns. The left most picket is formed by the sync patterns at the start of each row. If the sync pattern was not detected properly, that can be an indication for a burst error similar to the knowledge that a symbol of a picket column had to be corrected. The other three pickets are protected by the so-called Burst Indicator Subcode (BIS). This BIS-code has code words with 30 information symbols and 32 parity symbols giving a code word length of 62. The BIS code words are interleaved into three columns of 496 bytes each.

Note that both LDC code and the BIS code have the same number of parity symbols per code word and therefore only one Reed Solomon decoder is required to decode both codes.

The information symbols of the BIS-code form an additional data channel next to the main data channel. This side-channel in the BIS-columns contains addressing information. The addressing information is protected separately against errors with a Reed Solomon code that has code words with 5 information symbols and 4 parity symbols. This extra code is necessary to allow for fast and robust detection of the addresses, independent of the main ECC.

2.5 Address Format Using Groove Wobbles

Address Format Using Wobbled Groove

The BD-RE, as with CD-R, has a continuous groove formed spirally on itself for the laser beam to perform tracking control. Its track pitch (0.32 μm), however, is smaller than that of CD-R (1.6 μm). The role of this groove is not just tracking. It is also intended for the generation of write timing for the disc drive. More importantly, in addition, it is used to embed, on an unrecorded track itself, addresses identifying track positions in the whole area on the disc and auxiliary information inherent to the disc. For storing those information, the groove of the BD is modulated by wobbling. The amplitude of the wobble modulation is approximately ±10 nm in a radial direction of the disc.

The pit address system adopted by DVD-RAM and MO discs was one of the candidates in the investigation stage of address formats for the BD. The pit address system in general completely separates the reading/writing data area from the address area. This method ensures very high reliability during and after recording. In contrast, development of the BD format was promoted with a multi-layer system in mind since an early stage. Therefore, interlayer influences were thoroughly examined in the selection of the address format. As a result of evaluation, the continuous groove wobble system was adopted, as it is thoroughly free of interlayer influences.

The BD-RE writes very small high-density marks with precision. For this reason, the disc drive requires a highly stable and accurate recording clock signal. Therefore, the fundamental frequency component of wobbles is a single frequency and the groove is smooth and continuous. Given a single frequency, it is possible to generate a stable writing clock signal with ease from filtered wobble components. Since user data is written always in sync with the wobbles, the length of one wobble period is always proportional to the mark length of written data. Thus the disc capacity is naturally determined by the wobble size formed on the disc. (For example, the capacity of a single-layer disc is 23.3 GB if the wobble length is 5.52 um, and 25.0 GB if the wobble length is 5.14 um.

Single frequency-based wobbles are further modulated in order to add timing and address information. This modulation must be robust against various types of distortion inherent to optical discs. Roughly classified, the following four distortions can occur on optical discs.

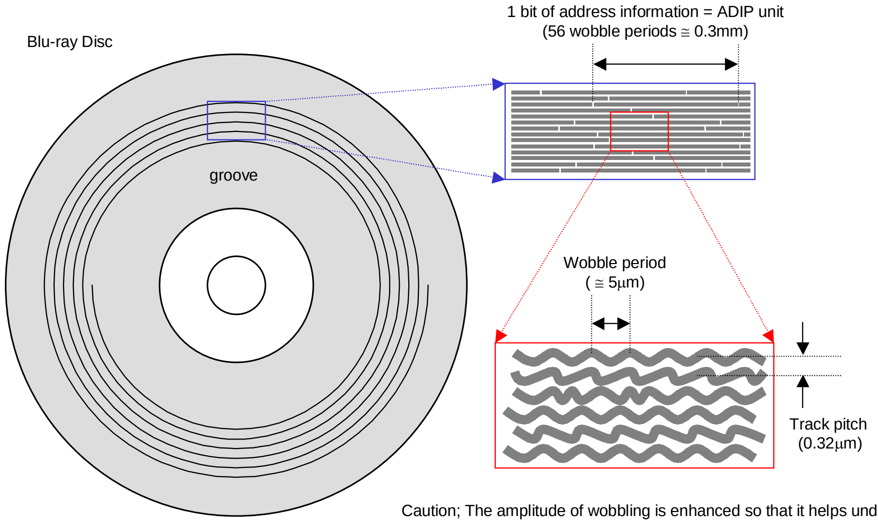
(1) Noise: Groove noise is caused by the recording film and the rough formation of tracking groove. Data crosstalk noise is caused by recorded data.
(2) Wobble shift: The phenomenon that the position of wobble detected by the disc drive relatively shifts from the normal position, resulting in decreased detection sensitivity. The wobble shift tends to occur immediately after seeking.
(3) Wobble beat: The wobble beat is produced by wobble crosstalk of adjacent tracks. The cause of the wobble beat is a shift in angular frequency of adjacent wobbles in the CLV format.
(4) Defect: A local flaw such as dust or scratch on disc surface.

A fundamental requirement in the development of the address format of BD was to take measures against all of these different types of distortions. Consequently, the BD uses a combination of two different wobble modulation systems in a configuration producing synergistic effects without side effects. This combination satisfies all the anti-distortion requirements, an outcome difficult to achieve using only one modulation system. More specifically, the BD has adopted a completely innovative address system combining minimum-shift-keying (MSK) modulation and saw-tooth-wobble (STW) technology, as explained later. The address format making use of MSK and STW is highly stable against the four types of distortion owing to each basic shape of the wobble.

Configuration of the ADIP Unit and Wobble Groove Shapes

Groove wobbles formed spirally on disc can be divided into units of address information bits embedded in itself (although they are successive), as shown in Fig. 2.5.1. This is known as the address in pre-groove (ADIP) unit. One ADIP unit is comprised of 56 wobbles. Fig. 2.5.2 shows a schematic diagram of the ADIP unit expressing "1" and "0" of one bit in address data by the MSK and STW combination.

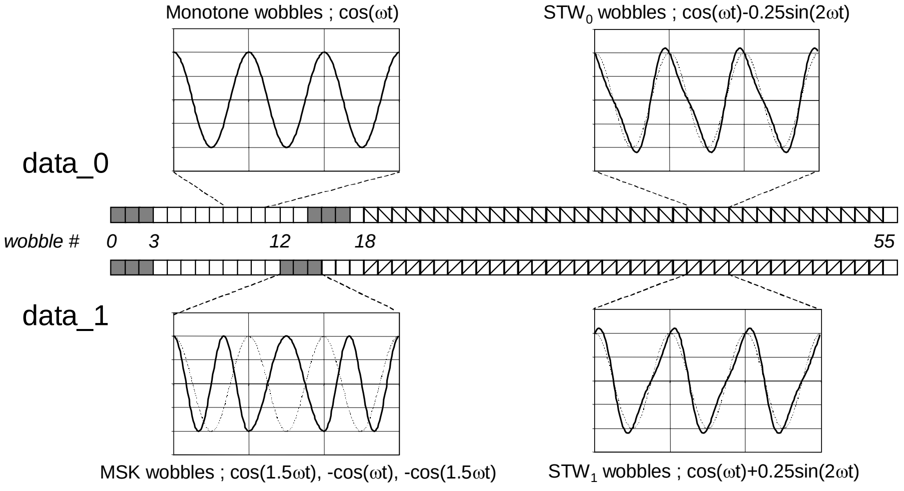
Fig. 2.5.1



Caution; The amplitude of wobbling is enhanced so that it helps understanding.

For the tracking of the laser beam, continues spiral groove is formed on the disc.
The groove is modulated with wobbling by cosine, MSK and STW in order to store the address information.

Fig. 2.5.2



Schematic representation of the ADIP units for data_0 and data_1. An ADIP unit has a length of 56 wobbles, which contain the first MSK mark for bit sync, the second MSK mark characterized by the difference of the position and 37 STWs characterized by the difference of the slope for data_0 or data_1.

The basic units of MSK and STW have the following shapes. The basic unit of MSK wobbles is three wobbles. The middle wobble of them has an inverted polarity in comparison with continuous cosine waves cos(ωt) (known as monotone wobble) other than MSK, and is sandwiched between cosine waves of a X1.5 frequency cos(1.5 ωt). MSK is made up of cosine instead of sine because, in the MSK modulation using phase inversion, smooth waveform connections will be achieved with adjacent wobbles without a discontinuous section. As a result, MSK requires a small number of frequency bands. As MSK uses one type of waveform alone, differences in waveform position are used as information.

STW waveforms are classified into two types. The waveform of data 0 has edges that rise steeply towards the outer side of the disc and fall gently towards the inner side of the disc. Conversely, the edges of the waveform of data 1 rise gently and fall steeply. The shape resembles saw teeth and that is why STW was so named. Mathematically, STW is expressed by the addition of the fundamental wave cos(ωt) and the second harmonic sin(2ωt) with a quarter-amplitude. The polarity of the secondary component in the case of data 0 is the inversion of data 1. Characteristically, however, zero-cross points, as in the case of monotone wobbles, have no influence on the clock phase reproduced from the fundamental wave component. Although sharp saw teeth can be expressed by the incorporation of higher harmonic components, the limitation to the secondary component makes it possible to keep the required band narrow for the disc mastering unit and to prevent degradation in high-frequency components caused by other signals.

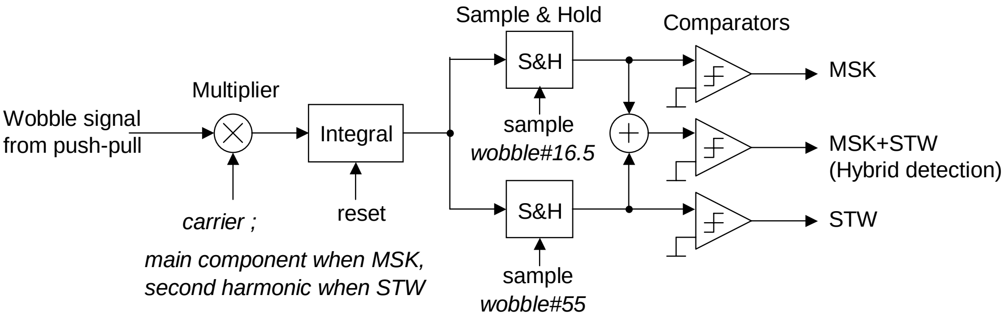
Every ADIP unit starts with MSK, as shown in Fig. 2.5.2. The starting MSK called "bit sync" serves as an identifier for the ADIP start point. The difference in the position of the next MSK represents 0 or 1 of data. More specifically, there are successive monotone wobbles between the bit sync and the second MSK, the number being 11 for data 0 and 9 for data 1, a 2-wobble difference in position. It should be noted that MSK utilizes local phase change of the fundamental wave. In other words, areas of no phase change must be predominant. Those areas are effectively used as STW, of which the phase of the fundamental wave does not change. In an ADIP unit, 37 wobbles from the 18th to the 54th are modulated by STW. Wobbles representing data 0 have edges rising steeply, and those representing data 1 have edges rising gently and are provided extensively. In order to ensure increased address reliability, the same information is stored in a single ADIP unit in different MSK and STW formats.

A series of 83 ADIP units forms an ADIP word expressing an address. One ADIP word contains 12-bit auxiliary data, reference (explained later), error correction code, as well as 24-bit address information. The BD allocates three ADIP words to each 64-Kbyte recording unit block (RUB) of main data for writing.

Detection Methods for and Characteristics of MSK and STW

The BD drive unit detects wobble signals from push-pull signals. Fig. 2.5.3 shows an example of circuit configuration. The drive unit is allowed to use MSK and STW independently or simultaneously to identify 0 or 1 of an ADIP unit.

Fig. 2.5.3



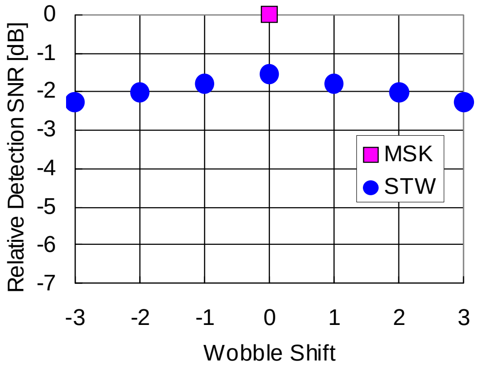
An example of the heterodyne detection circuit for the MSK marks and the STWs. Both of the MSK marks and STWs can be detected using the common circuit by only changing frequency of the carrier supplied to the multiplier.

MSK and STW although apparently different can be detected using the same heterodyne circuits (consisting of a carrier multiplier, integrator, sample-and-hold, and comparator). Increased detection performance is achieved by a hybrid detection method in which integrals of MSK and STW are added up.

Their detection methods differ in that MSK uses the fundamental wave (957 KHz) as the carrier for multiplication, while STW used the second harmonic (1,913 KHz). The only other difference is in the timing signal used to operate each circuit. MSK and STW are highly compatible with each other in terms of detection circuits.

Fig. 2.5.4 plots the relationship between wobble shift amount and relative Signal to Noise Ratio (SNR) of detection sensitivity, MSK and STW being detected independently. If no wobble shift occurs on the one hand, the SNR of MSK detection is 1.6 dB higher than STW. A high SNR implies excellent noise immunity. If, on the other hand, a wobble shift occurs, MSK loses detection sensitivity while the detection sensitivity of STW is stable against ±3 wobble shifts. Thus, MSK detection is robust against noise, while STW detection is highly sound to wobble shifts. These contrasting characteristics originate in the form the location in the groove.

Fig. 2.5.4



Calculated signal-to-noise ratio for detection of MSK marks and the STWs using the circuit of Figure 3 in case of no cross talk from adjacent tracks as a function of wobble shift.

MSK stores information in a local area making use of strong phase change of the fundamental wave and is therefore excellent in SNR. STW is not prone to performance degradation caused by positional shifts as its information is distributed in a wide area spanning 37 cycles. In contrast, MSK provides better position information as bit sync for finding the head of an ADIP unit. STW laid out in a wide area is insensitive and tough to local defects. An outcome of the combination of MSK and STW in an address format is the achievement of substantial robustness against different types of distortions, such as noise and defects, and satisfactory high performance for wobble shifts and correct positioning.

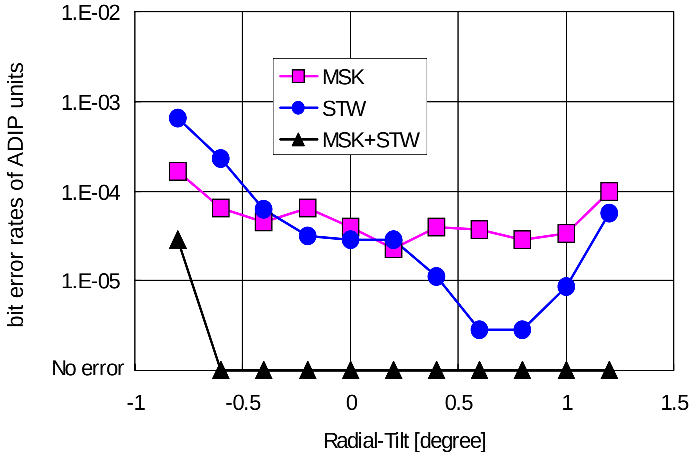
Reference ADIP Unit

Wobble beats, which are beats at the fundamental frequency of wobbles, occur substantially as the groove on BD is a narrow-pitched groove. These beats modulate both the amplitude and phase of the detected single-frequency component. Consequently, detection quality of both MSK and STW degrades due to the beats. Hence the physical length of one wobble cycle was examined to minimize the influence of beats and was established to be equivalent to 69 writing channel clock signals. Furthermore, reference ADIP units, which are inserted at every 5 ADIP units, can correct the influence of beats. The reference ADIP unit is comprised of STW of data 0. Since the unit is known to be 0 in advance, it becomes possible to correct a phase shift so that the detected value is precisely data 0.

Experimental Results of Margin of Error

Fig. 2.5.5 shows bit error rates of ADIP units for radial tilt in the detection, by MSK only, STW only, and the combination of them, of data on written tracks of a test disc. The measurement actually involved all influences such as noise by written data, wobble shifts, defects, and crosstalk from adjacent tracks. Notwithstanding those influences, the system achieved an ADIP bit error rate of 10^{-4} or less regarded necessary for the system, in a wide range. As a matter of practicality, the necessary margin of error of address information is ensured within approximately ±0.7 degrees of radial tilt. In comparison, the necessary margin of error of address information is ensured in a far wider range, providing high reliability.

Fig. 2.5.5



Error rates of ADIP units of a sample disc as function of radial tilt. The measurements are done with ADIP units of $3.5*10^5$ sample points for written tracks. It is enough to perform in the practical use if the error rates are under 10^{-4}.

Reference:

"Wobble-address format of the Blu-ray Disc", S. Furumiya et al., Techn. Digest ISOM/ODS 2002