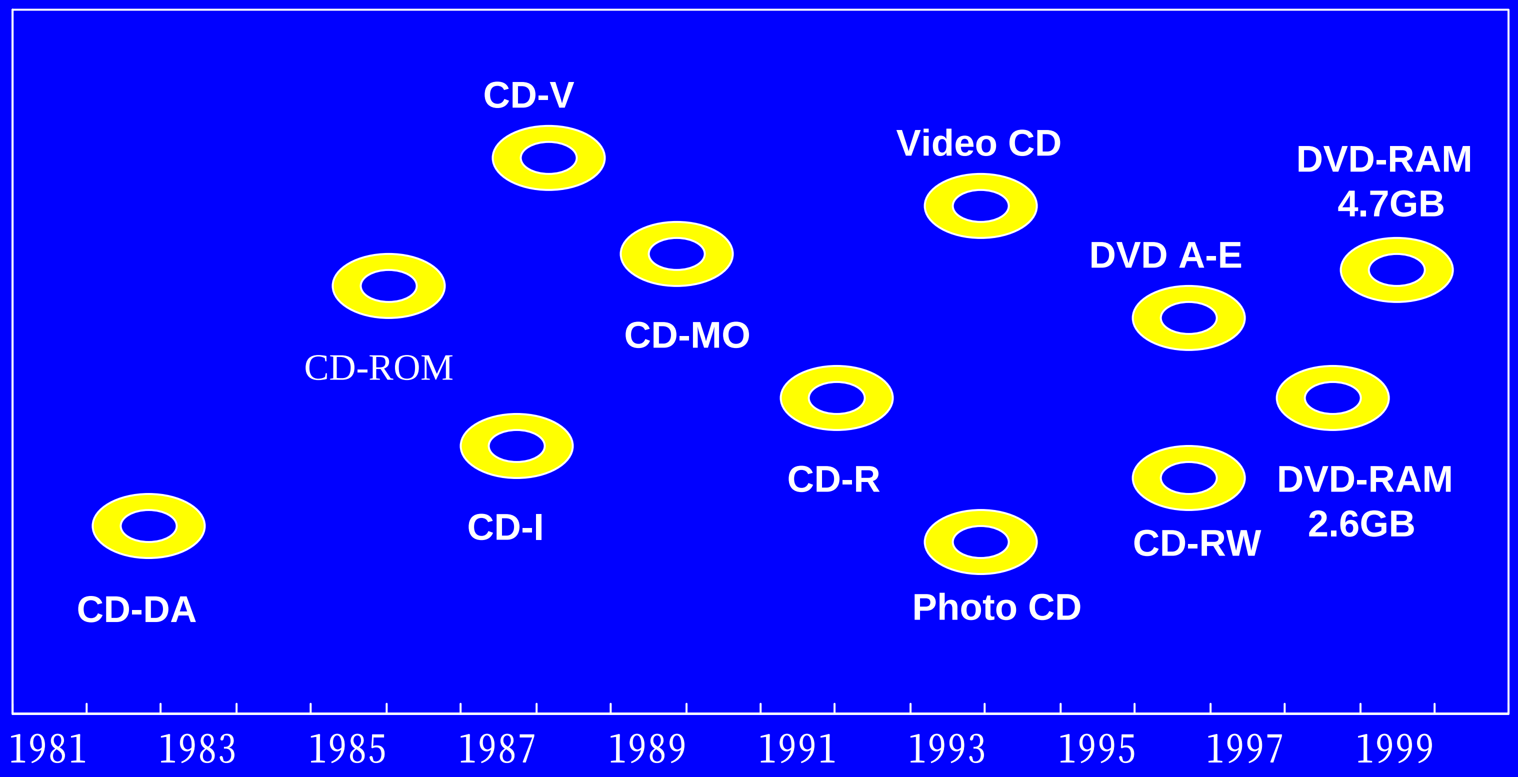
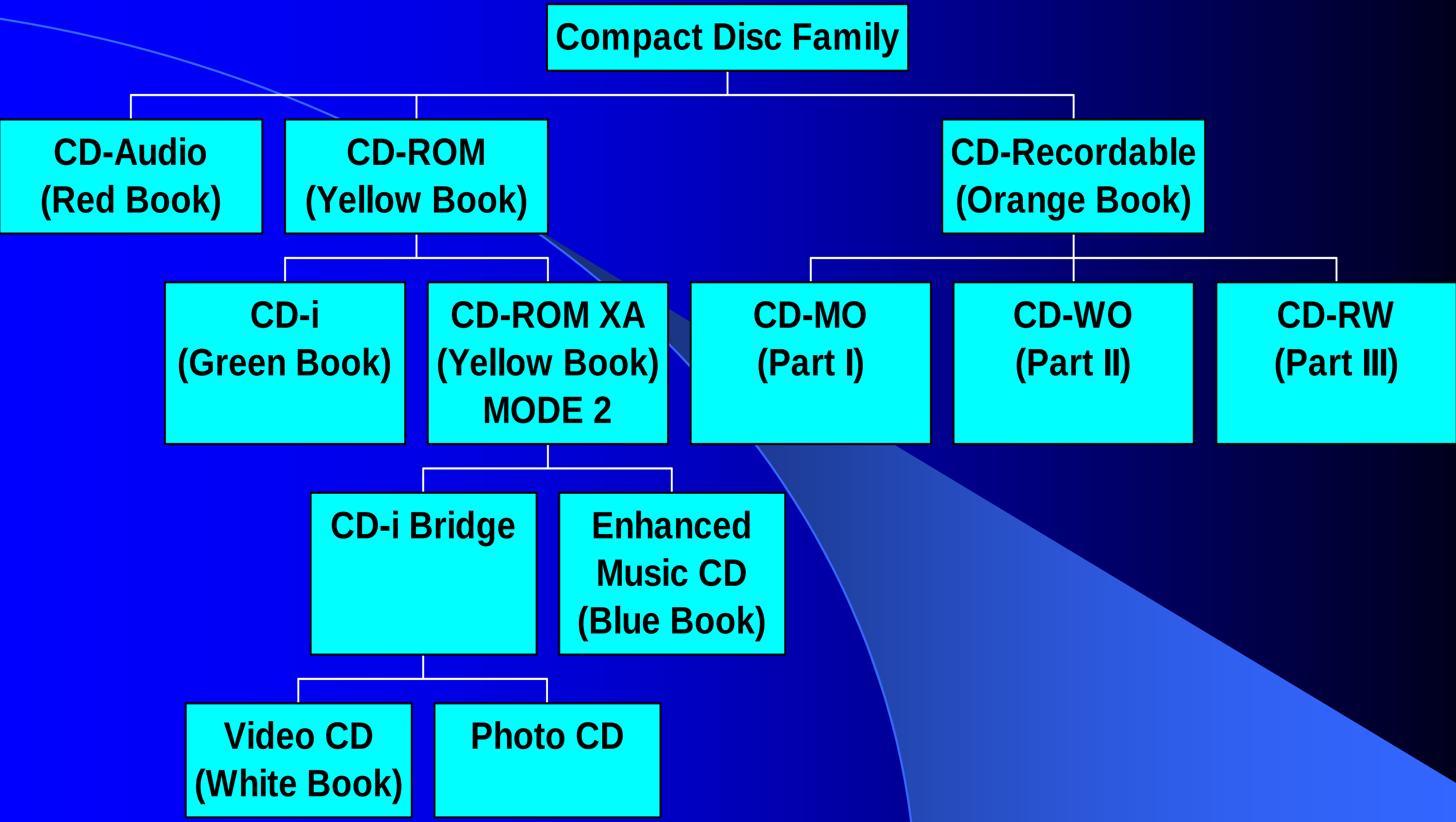
Optical Storage Technology

The Compact Disc

History of the Compact Disc



Family of the Compact Disc

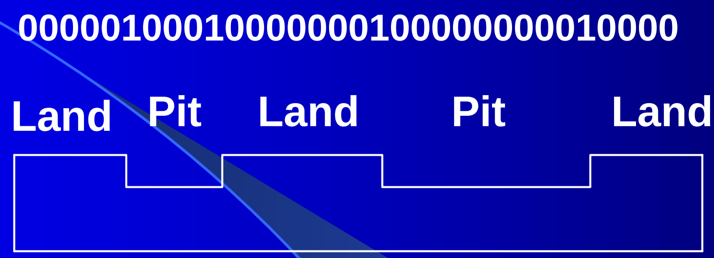


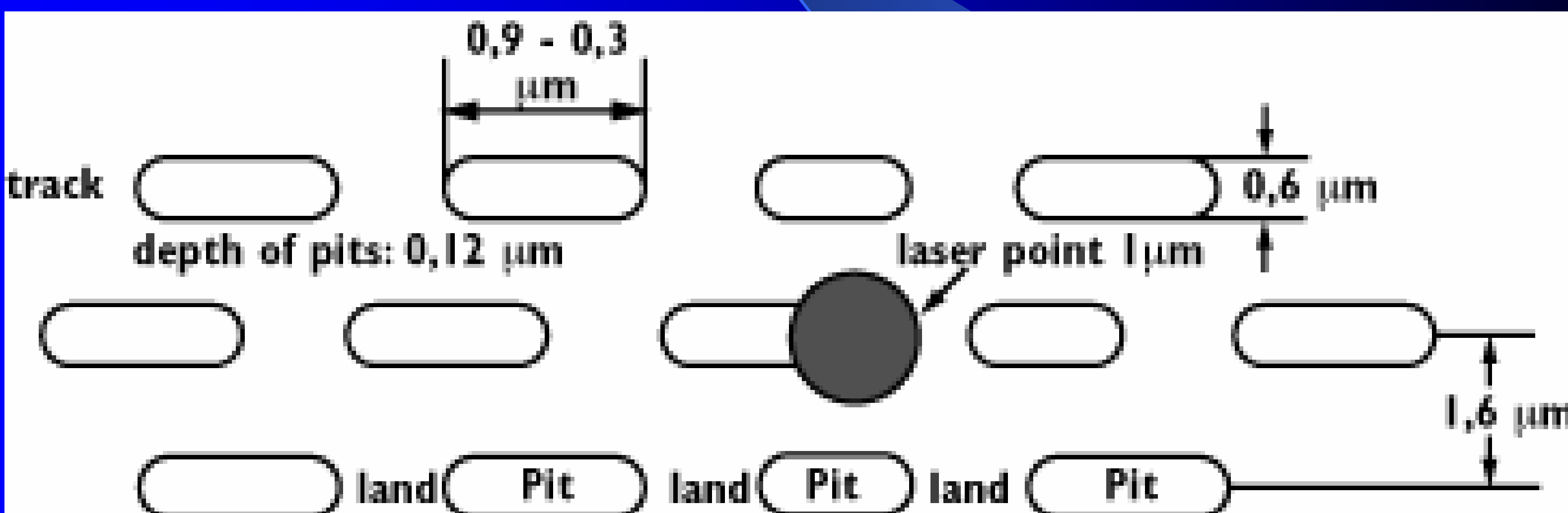
Compact Disc Overview

- An audio disc stores a stereo signal comprised of **two 16-bit** data words sampled at **44.1 KHz**; thus **1.41 million bits** per second of audio data are output from the player.
- **Error correction**, **synchronization**, and **modulation** are required, which triple the number of bits stored on a disc.
- The **channel bit rate**, the rate at which data is read from the disc, is **4.3218 Mbps**.
- A disc containing an hour of music holds about **15.5 billion channel bits**.
- Apart from modulation and error correction overhead, a CD-DA disc holds a maximum of **6.3 billion bits**, or **783 million bytes** of user information.

Compact Disc Overview

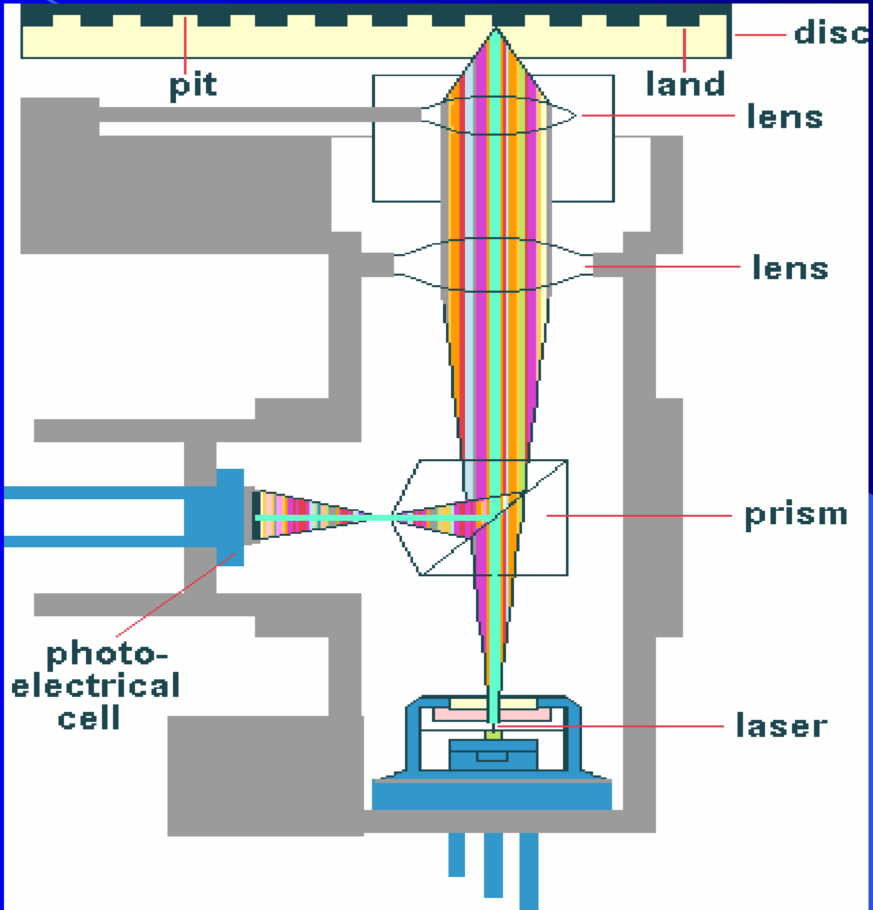
- Information is contained in pits impressed into the disc’s plastic substrate.





Compact Disc Overview

- Pits are encoded with **eight-to-fourteen modulation (EFM)** for greater storage density, and **Cross-Interleave Reed-Solomon code (CIRS)** for error correction.



Disc specifications

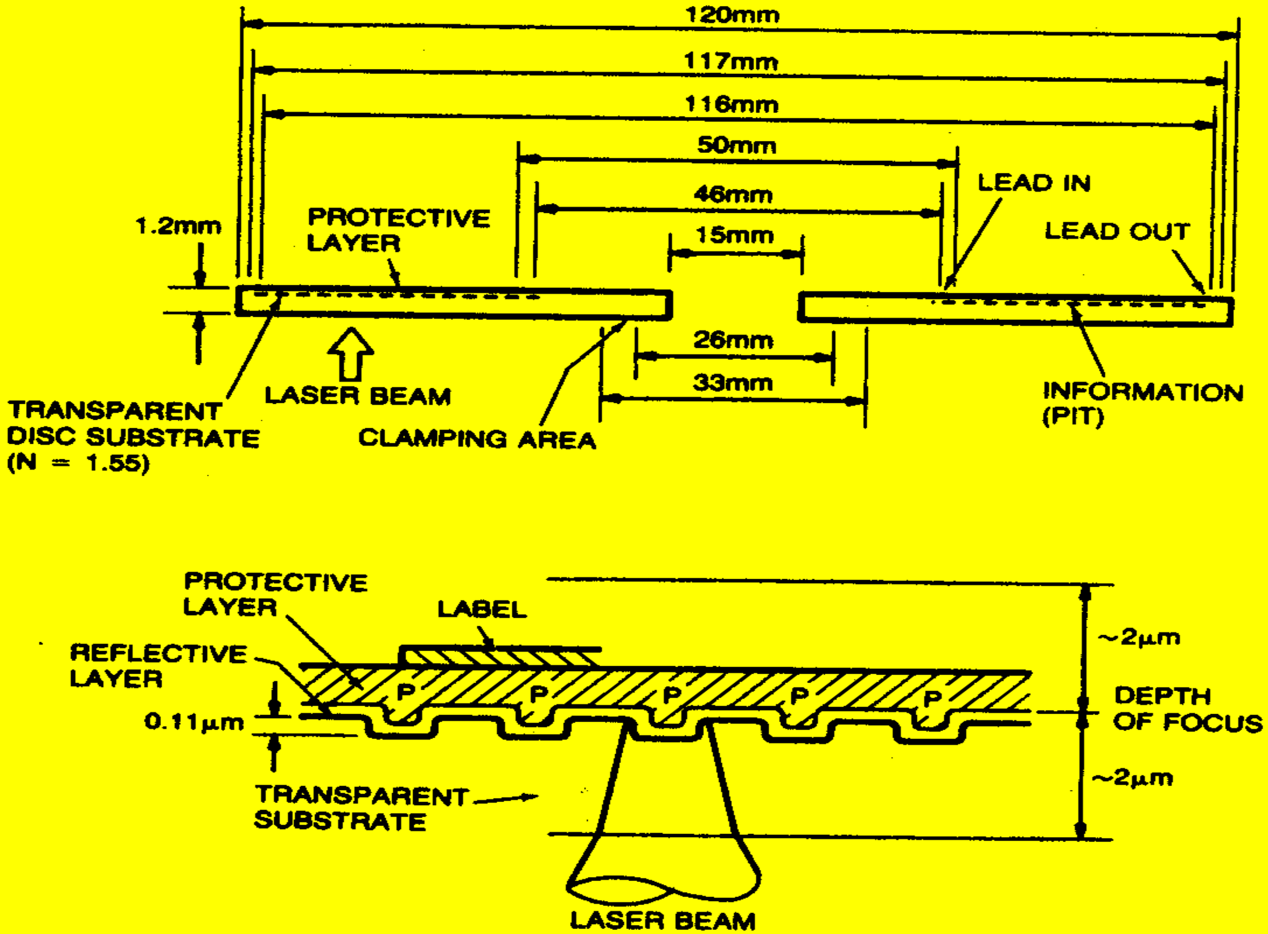


Figure 9.1 Physical specification of the compact disc showing disc dimensions and relief structure of data pits. (*Sony Corporation*)

Disc specifications

- The data reference is metallized. The reflective flat surface, called **land**, typically causes 90% of the laser light to be reflected back to the pickup.
- The construction of the CD is **diffraction-limited**, that is, the wavelength of the laser light would not permit smaller formation.
- Inside the polycarbonate substrate, with a refractive index of **1.55**, the laser's wavelength is reduced from 780 nm to **500 nm**.
- The height of each bump is between **0.11 to 0.13 μm**, which is approximately **1/4** of the laser's wavelength in the substrate.

Disc specifications

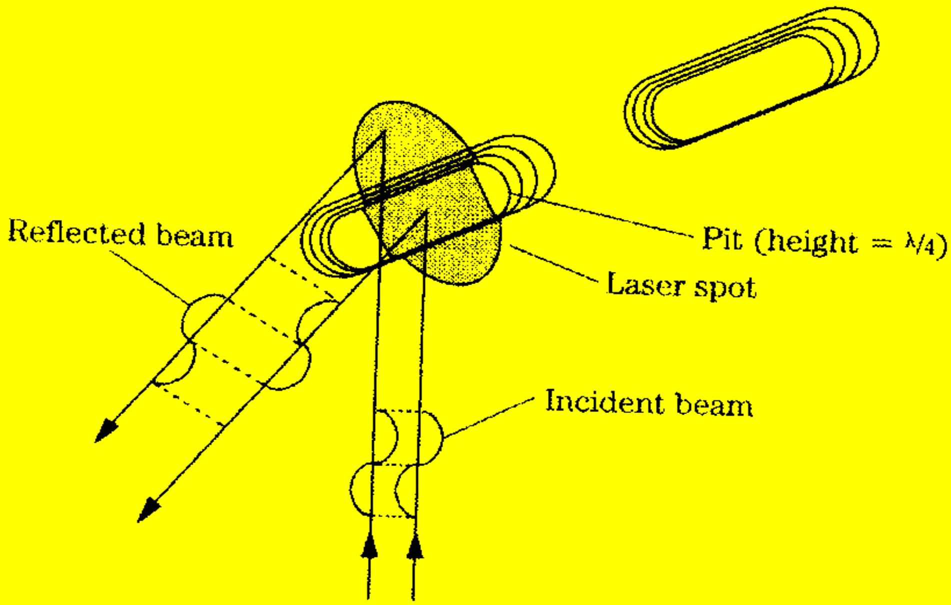


Figure 9.3 The laser spot reads data as an intensity modulation of its reflected beam. The phase structure of the data surface places the pit height about $\lambda/4$ over the land surface; this creates destructive interference in the reflected beam.

- A disc rotates with **constant linear velocity (CLV)**.
- The CLVs used in different discs can range from **1.2 to 1.4 m/s**. The CD player is indifferent to the actual CLV; it **automatically regulates** the disc rotational speed to maintain a constant channel bit rate of **4.3218 MHz**.

Data Encoding

- The audio program is represented as **16-bit PCM** data. The data stream must undergo **CIRC error correction** and **EFM modulation**, and **subcode** and **synchronization** words must be incorporated as well.
- A **frame** is the smallest complete section of recognizable data on a disc.

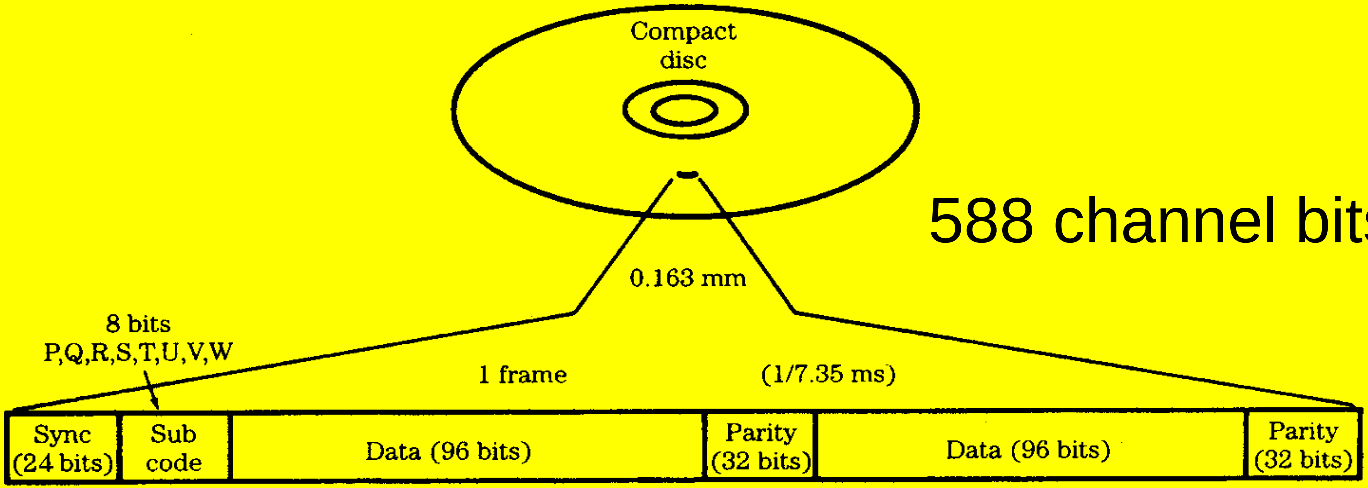


Figure 9.4 Elements of a CD frame shown without EFM modulation and interleaving. All data except the sync word undergo EFM modulation to create a total of 588 channel bits.

Data Encoding

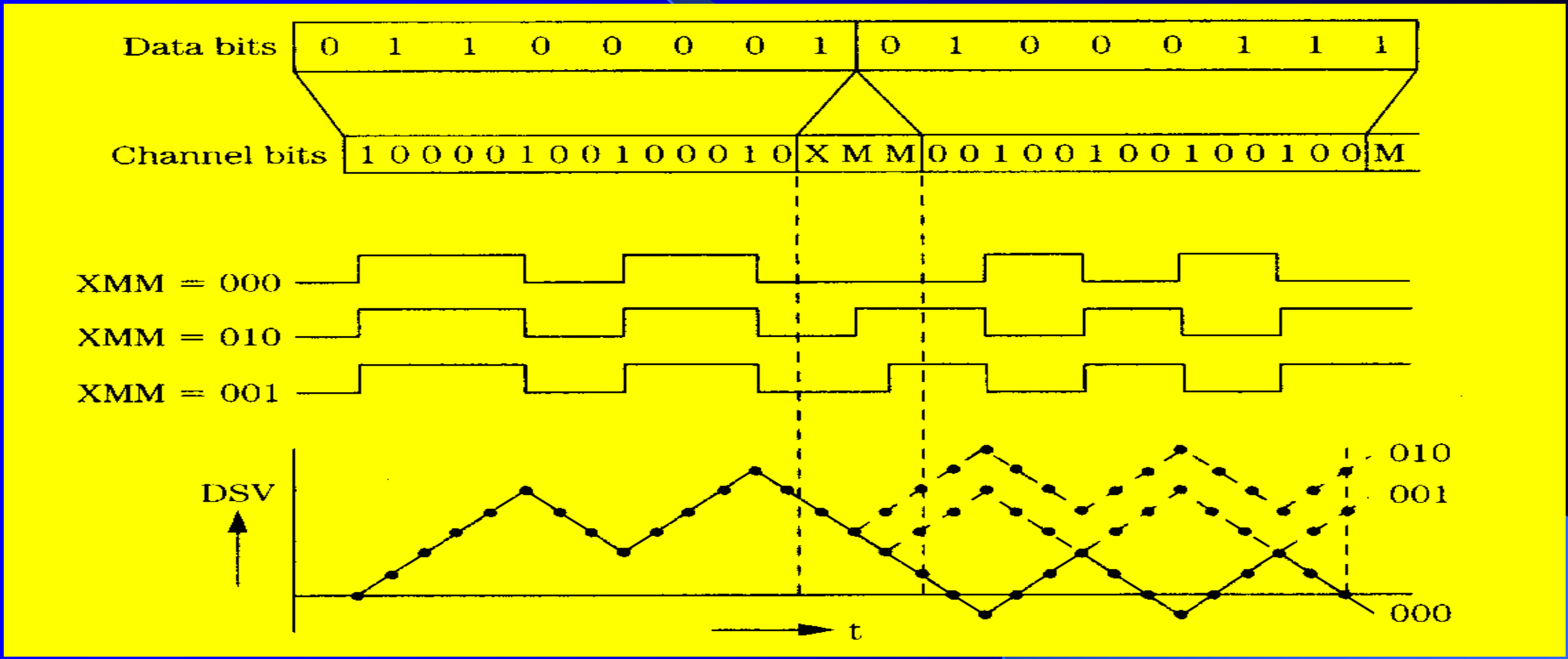
- **Six** 32-bit PCM audio sampling periods (left and right channel) are grouped in a frame. $\rightarrow$ **192 audio bits**.
- The 32-bit sampling periods are divided to yield four **8-bit audio symbols**.
- To scatter possible errors, the symbols from different frame are **interleaved** so that the audio signals in one frame originate from different frames.
- **Eight 8-bit parity symbols** are generated per frame. The interleaving and generation of parity bits constitute the **error correction coding** based on the CIRC.
- One 8-bit (P,Q,R,S,T,U,V,W) **subcode** symbol is added per frame. **P and Q** contain information detailing total number of selections on the disc, their beginning and ending points, index points within a selection and others.

Data Encoding

- R,S,T,U,V and W are available for other applications, such as encoding **text** or **graphics** information on audio CDs.
- **EFM modulation** gives the bit stream **specific patterns** of 1s and 0s, thus defining the lengths of pits and lands.
- EFM permits a high number of channel bit transitions for arbitrary pit and land lengths. This increases **data density** and helps facilitate control of the **spindle motor speed**.
- Block of **8** data bits are translated into blocks of **14** channel bits.
- The 8-bit symbols required **2^8=256** unique patterns, and of the possible **2^{14}=16,384** patterns in the 14-bit system, 267 meet the pattern requirements; therefore, 256 are used and 11 discarded.

Data Encoding

- Blocks of 14 channel bits are linked by the **three merging bits** to maintain the **proper run length** between words, as well as suppress dc content, and aid clock synchronization.
- The **digital sum value (DSV)** is used to monitor the accumulating dc offset.



Data Encoding

- The ratio of bits before and after modulation is **8:17**. The resulting channel stream produces pits and lands that are at least **two** but no more than **ten** successive 0s long.
- 3T, 4T,…, 11T where T is one channel bit period. The pit / land lengths vary from **0.833 to 3.054 μm** at a track velocity of **1.2 m/s**, and from **0.972 to 3.56 μm** at a track velocity of **1.4 m/s.**

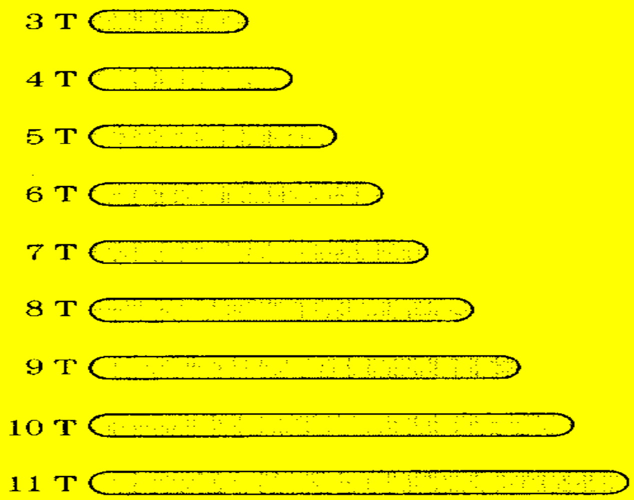


Figure 9.6 The complete collection of pit (and land) lengths created by EFM ranges from 3T to 11T. Minimum pit length is 0.833 to 0.972 μm; maximum pit length is 3.054 to 3.56 μm, depending on velocity (1.2 to 1.4 m/s).

Data Encoding

- Data bits → Channel bits → Nonreturn to zero (NRZ) → Nonreturn to zero Inverted (NRZI).

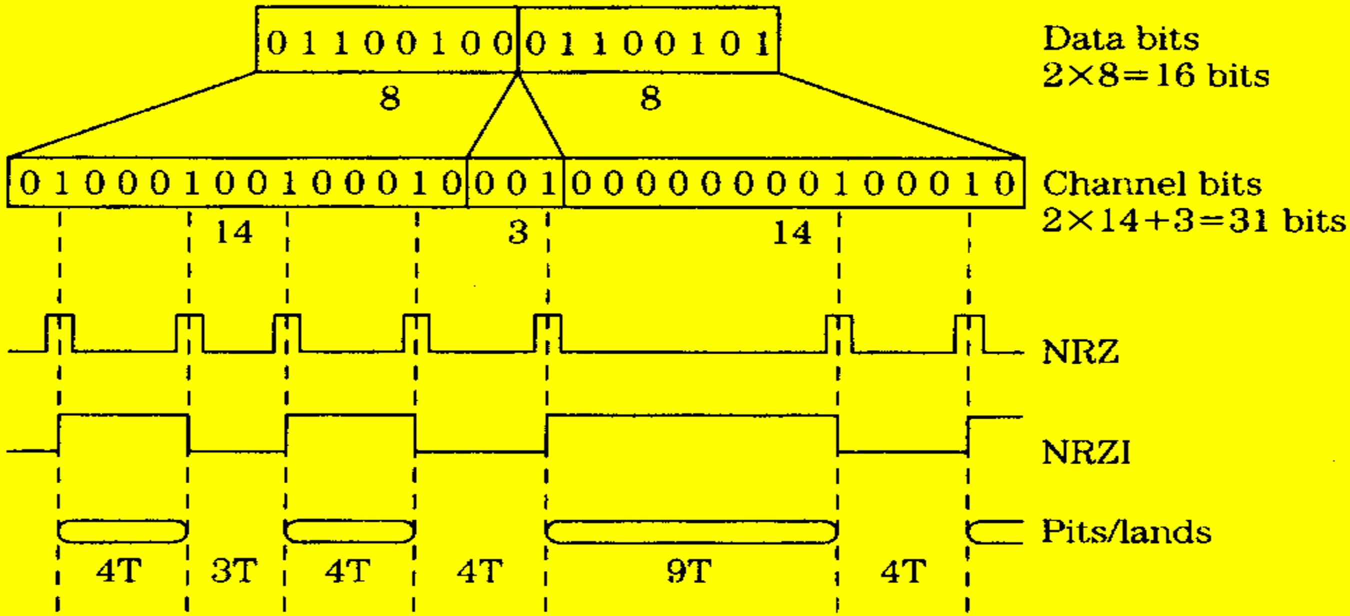


Figure 9.7 Each 8-bit half-sample undergoes EFM, three merging bits concatenate 14-bit words, the NRZ representation is converted to NRZI, and transitions are represented as pit edges on the disc.

Simple and Group-code waveform

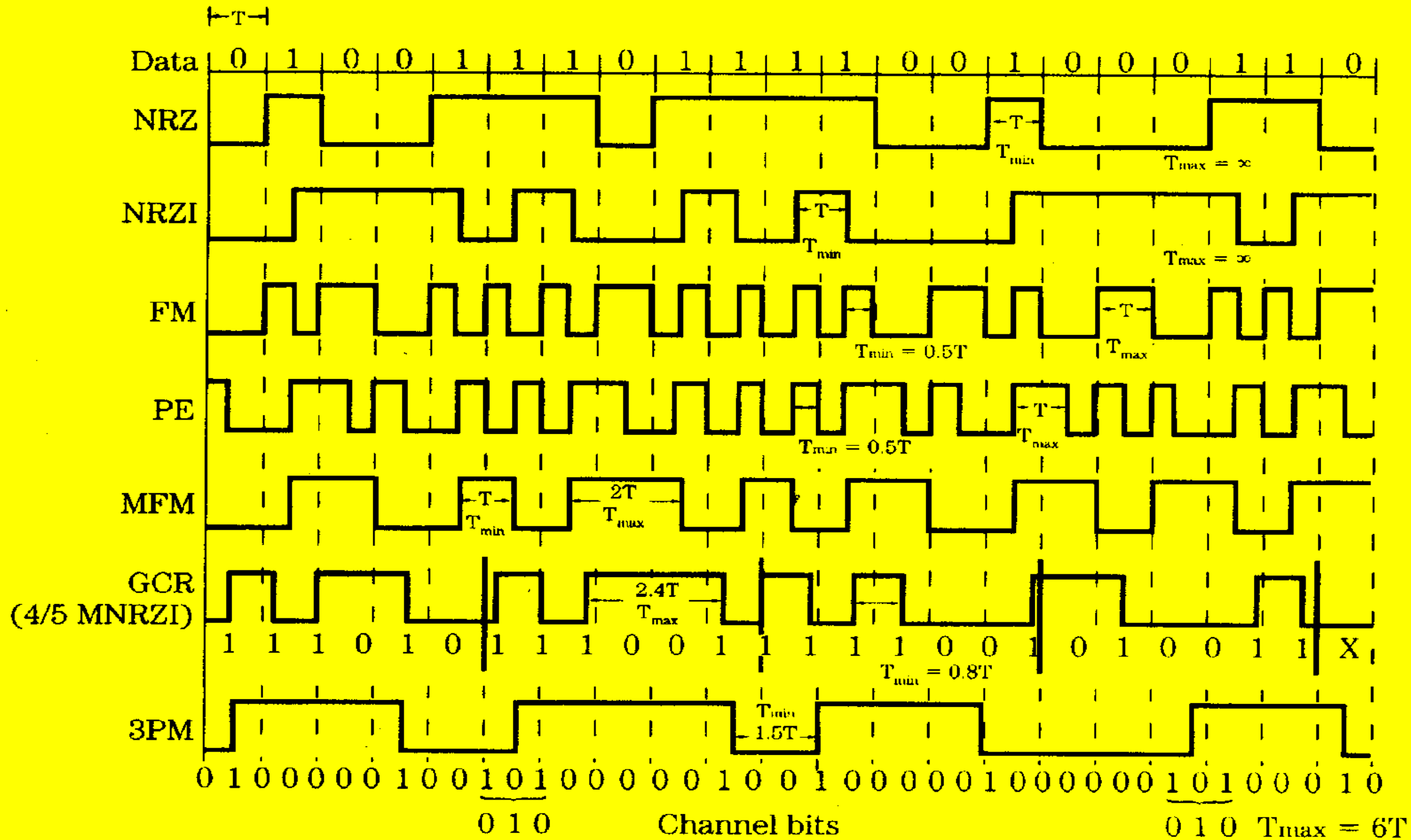
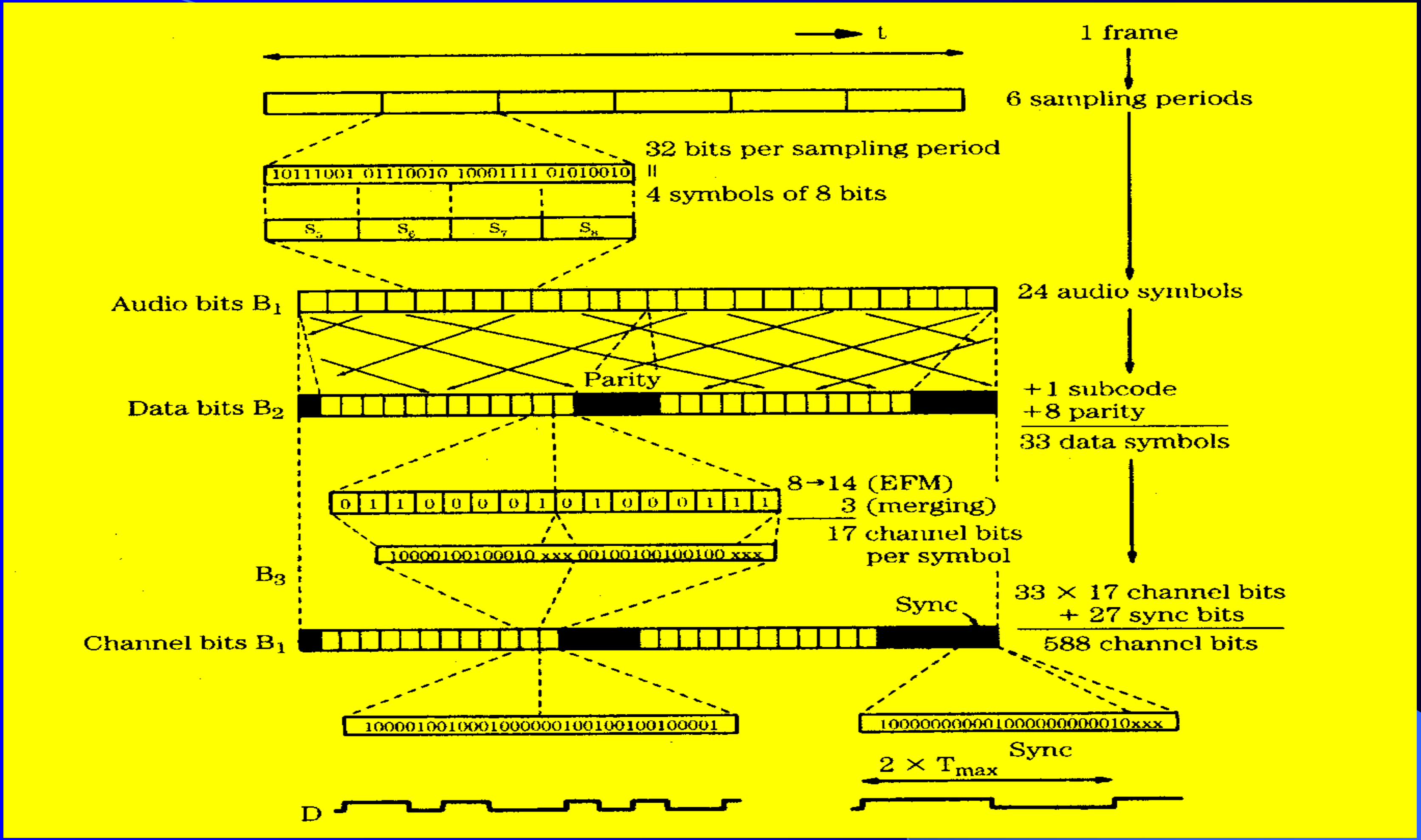


Figure 3.17 A comparison of simple and group-code waveforms for a common data input.

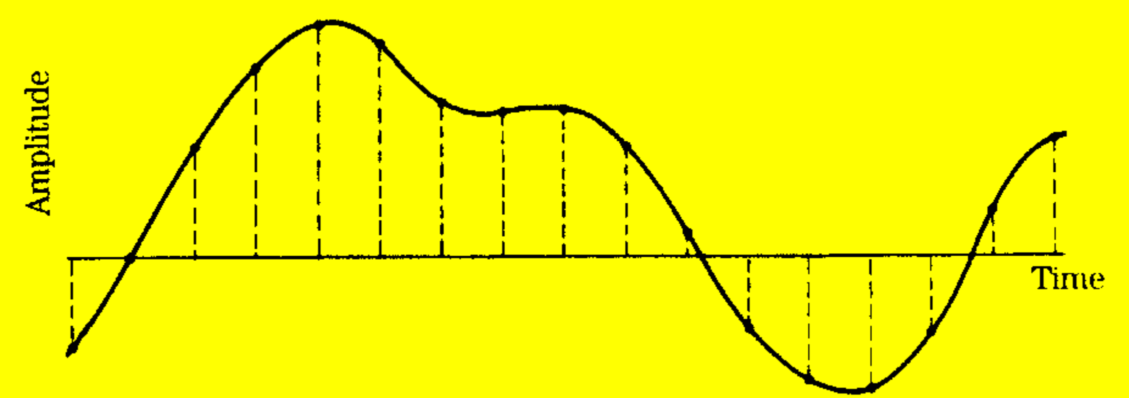
Data Encoding

- A **synchronization pattern** is placed at the beginning of each frame to identify the start of each frame.



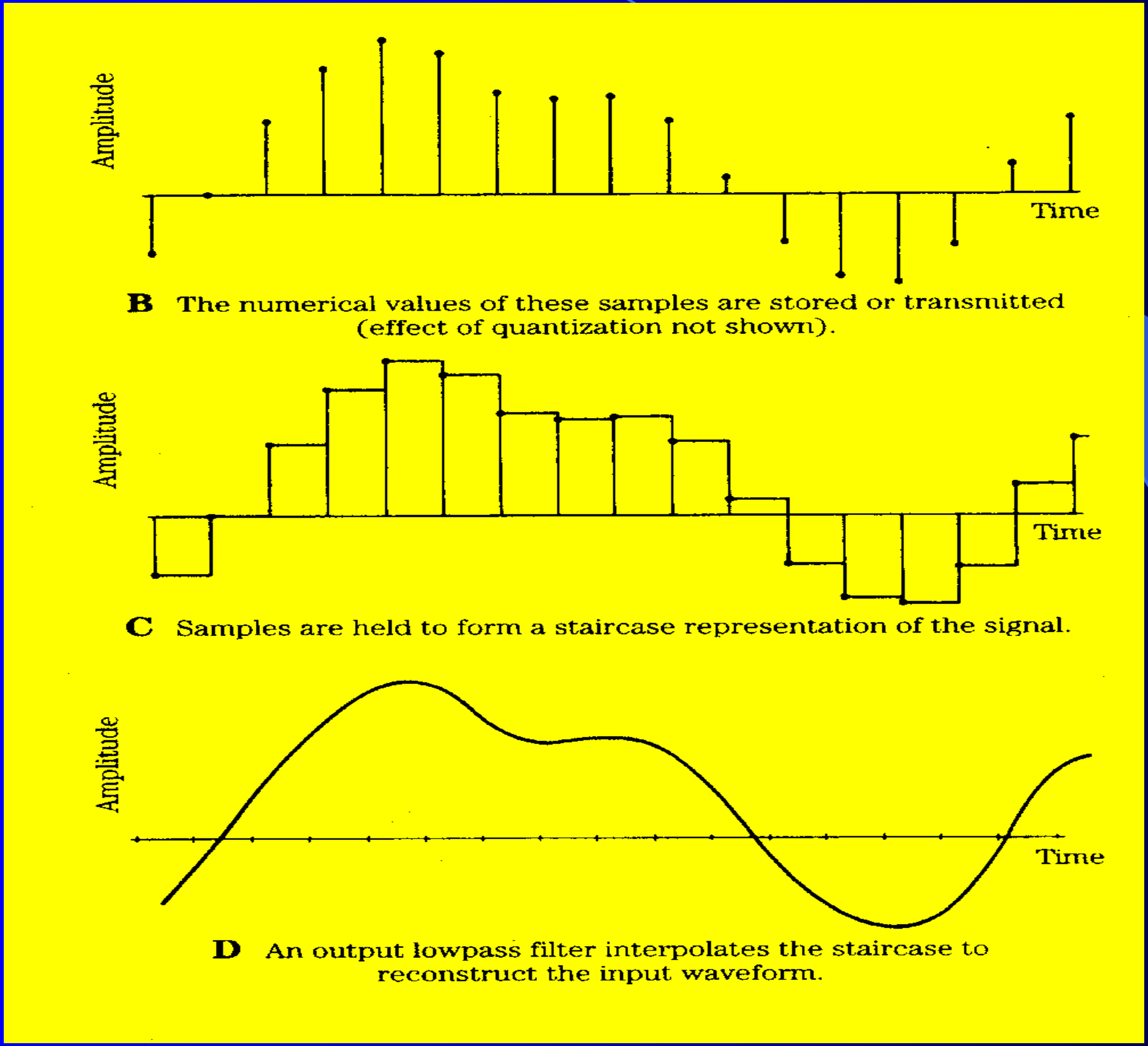
Digital Audio

- **Sampling** represents the time of the measurement, and **quantization** represents the value of the measurement, or the amplitude of the waveform at sampling time.
- A sampling frequency of **44.1 KHz** is selected for the compact disc, while the **16-bit** data quantizing word is used.
- The sampling frequency as well as the number of bits in the quantizing word determine the accuracy of A/D converter.



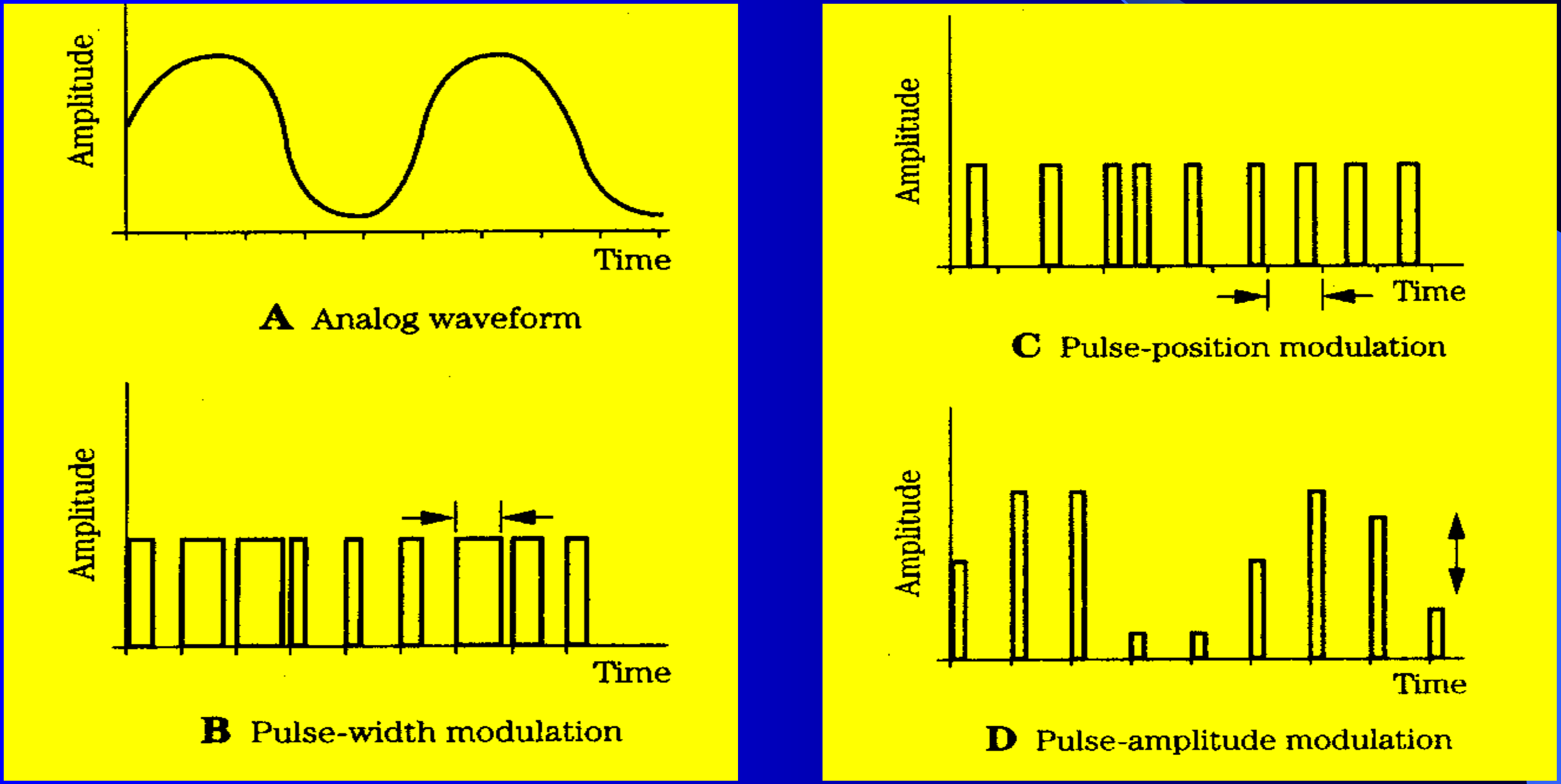
A The input analog signal is sampled.

Digital Audio



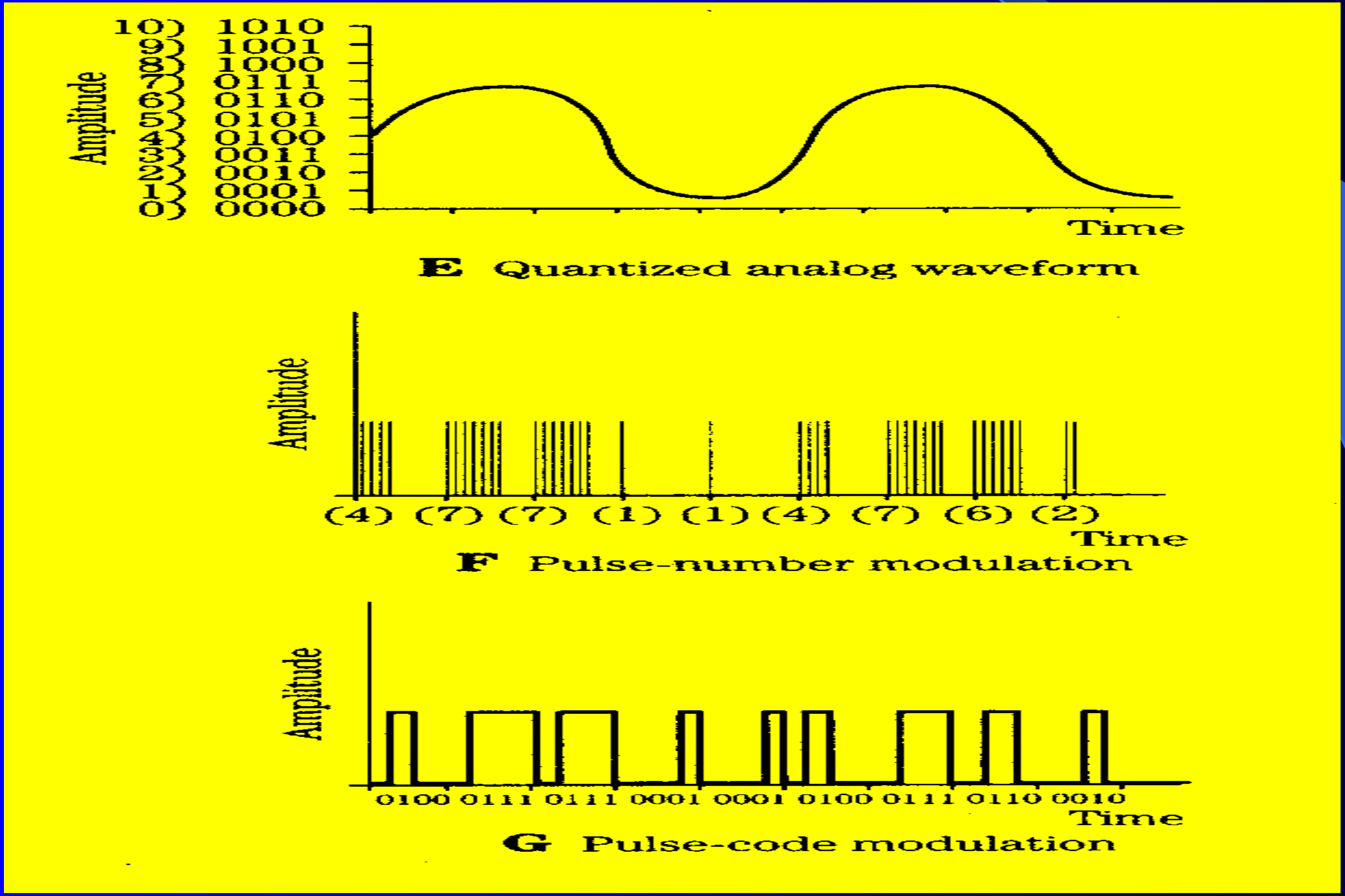
Modulation

- Modulation is nothing more than a means of encoding information for the purpose of transmission or storage.



Modulation

- In **Pulse-Code Modulation** (**PCM**), the input signal must undergo sampling, quantization, and coding.



Channel Code

- Channel code modulation must occur prior to storage or transmission. The channel code defines the logical 1 and 0 of the input information.
- **Return to zero (RZ)** code : sends a pulse for each 1 and does not send a pulse for a 0.
- **Nonreturn to zero (NRZ)** code : 1s and 0s are represented directly as high and low level.
- **Nonreturn to zero inverted (NRZI)** : only 1s are denoted with amplitude transitions; no transitions occur for 0s.
- Binary **frequency modulation (FM)** : there are two transitions for a 1 and one transition for a 0.
- **Phase encoding (PE)** : a 1 is coded with a positive-going transition, and a 0 id coded with a negative-going transition.

Channel Code

- **Modified frequency modulation (MFM)** : a 1 is coded with either a positive- or negative- going transition in the center of a bit period, for each 1. There is no transition for 0s.
- **Simple codes** such as NRZ and NRZI code one information bit into one channel bit. **Group codes** use code tables to convert groups of input words into pattern of output words.
- Group codes also can be considered as **run-length limited (RLL)** codes. They specify a minimum number ***d*** and maximum number ***k*** of 0s between two successive 1s.
- RLL codes use a set of rule to convert the information bit stream into a stream of channel bits by defining some relationship between them.

Channel Code

- **Group coded recording (GCR)** : data is parsed into 4 bits, coded into 5-bit words using a look-up table. It is also known as 4/5 MNRZI code.
- **Three-position modulation (3PM)** code : is a **(2,7) run-length limited** adaptive code. Three input bit are converted into a 6-bit output word.
- **Eight-to-fourteen modulation (EFM)** code is used to store data on a compact disc. It is an efficient and highly structured **(2,10) RLL** code.

Channel Code

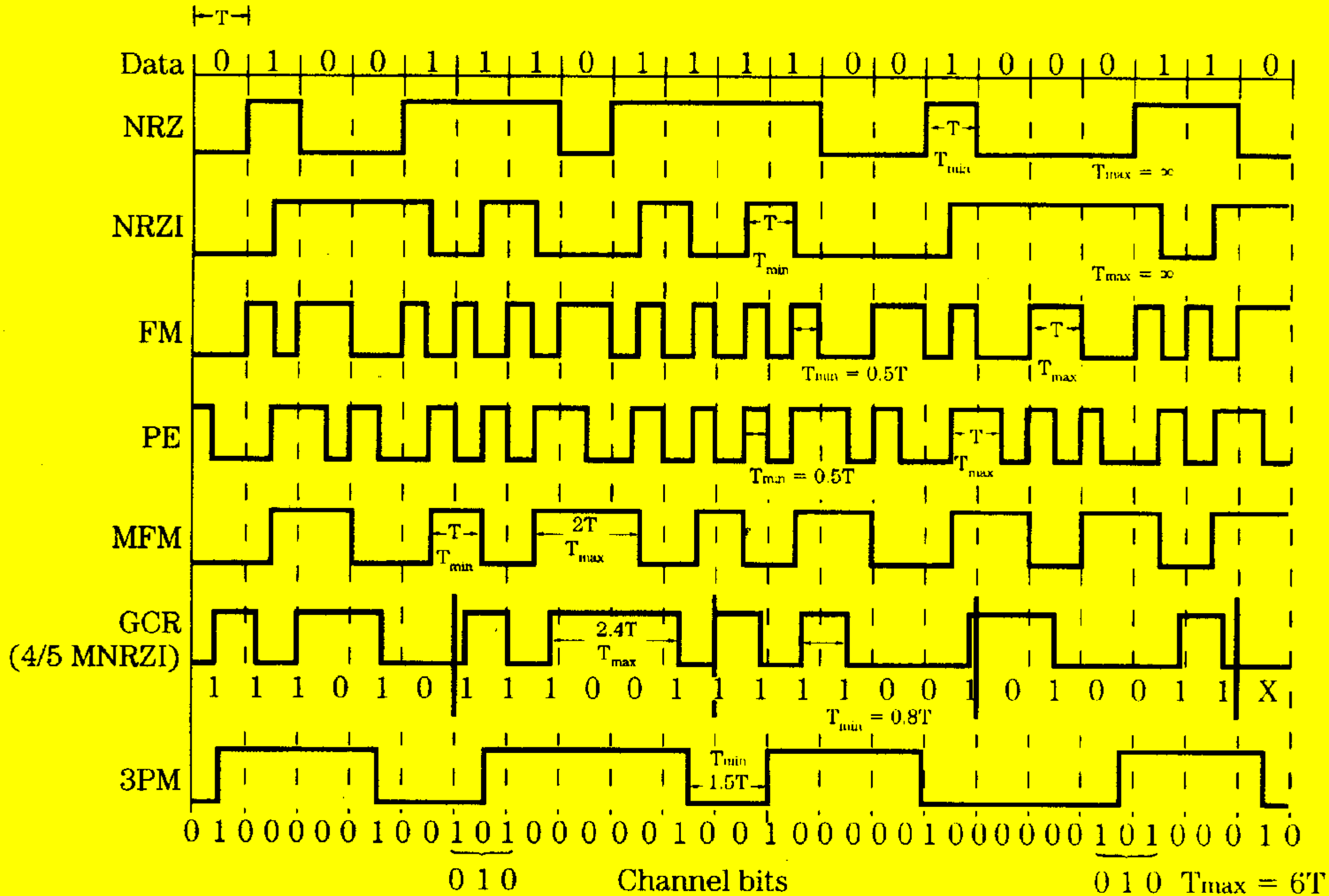


Figure 3.17 A comparison of simple and group-code waveforms for a common data input.

Channel Code

TABLE 3.1 Conversion for the GCR (or 4/5 MNRZI) code. Groups of four information bits are coded as 5-bit patterns, and written in NRZI form.

Data bit	Channel bit
0000	11001
0001	11011
0010	10010
0011	10011
0100	11101
0101	10101
0110	10110
0111	10111
1000	11010
1001	01001
1010	01010
1011	01011
1100	11110
1101	01101
1110	01110
1111	01111

TABLE 3.2 Conversion for 3PM (2,7) code. Three input bits are coded into a 6-bit output word in which the minimum interval is maintained at 1.5*T* through pattern inversion.

Data bit			Channel Bit					
			P1	P2	P3	P4	P5	P6
0	0	0	0	0	0	0	1	0
0	0	1	0	0	0	1	0	0
0	1	0	0	1	0	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	0	0	1	0	0	0
1	0	1	1	0	0	0	0	0
1	1	0	1	0	0	0	1	0
1	1	1	1	0	0	1	0	0
	|←T→|			|←T→|				

Optical Design – optical pickup

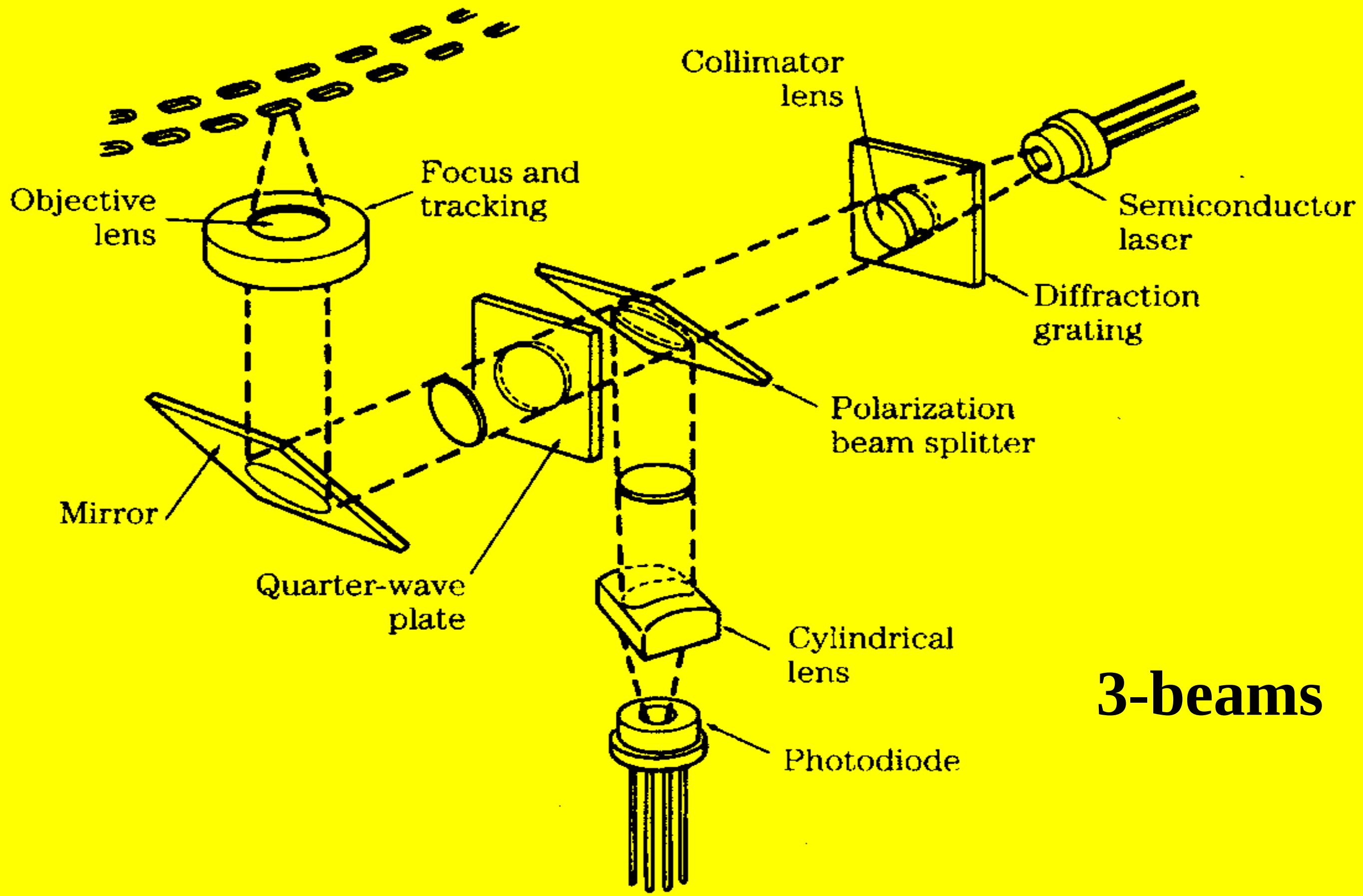
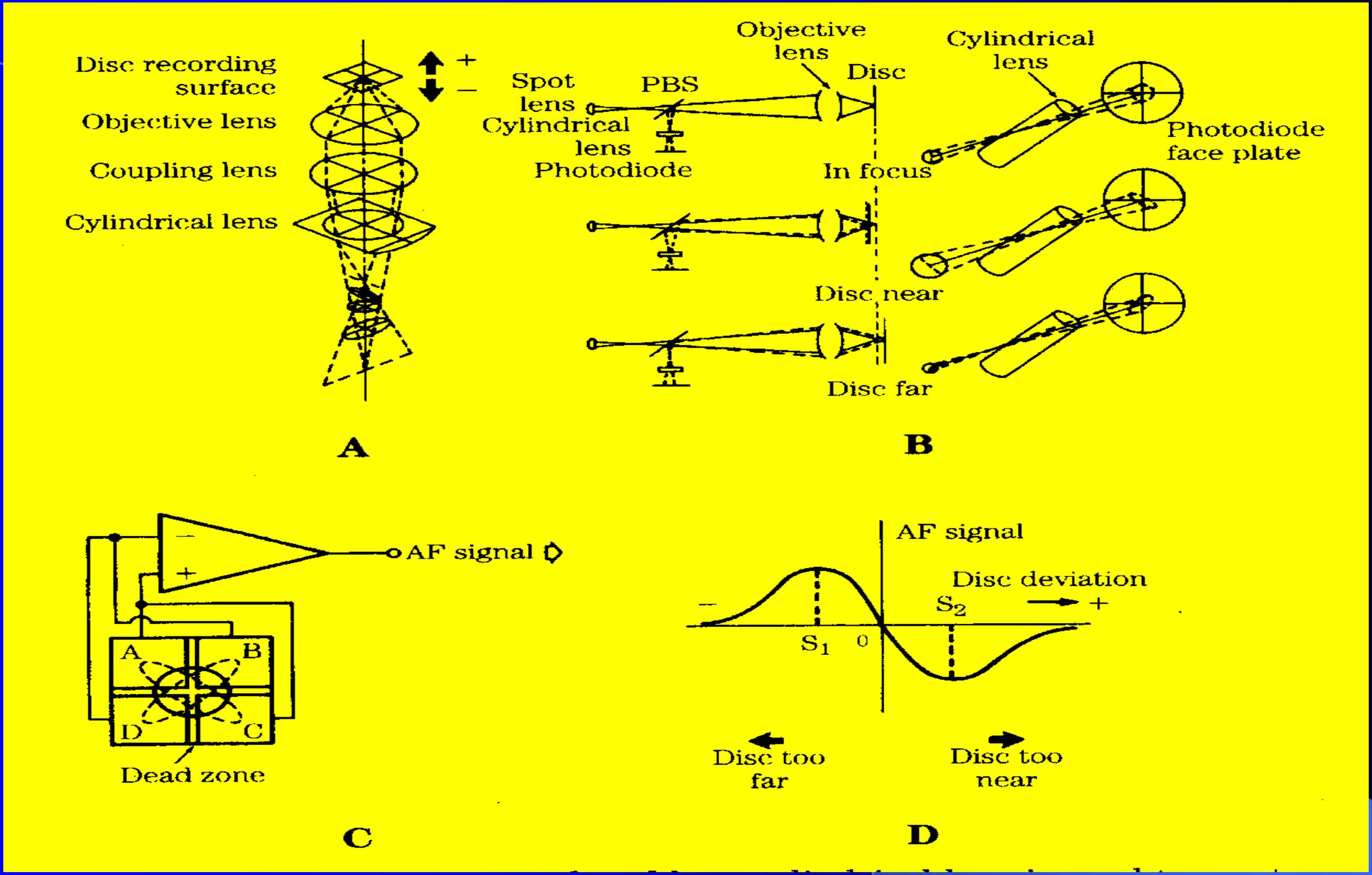


Figure 9.9 Diagram showing the optical elements in a three-beam optical pickup. (*Sony Corporation*)

Optical Design – Autofocus



Optical Design – Autotracking

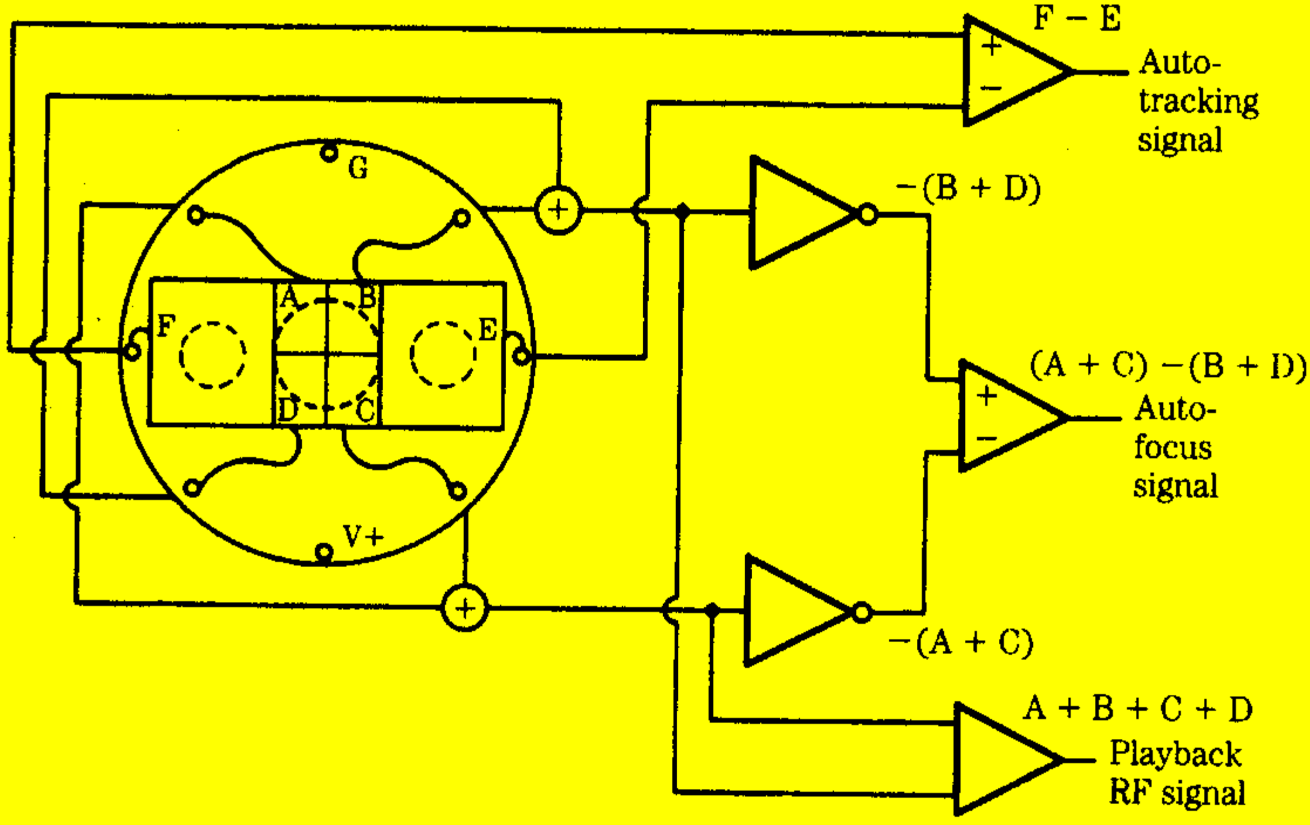


Figure 9.11 The four quadrant photodiode (A, B, C, D) is used for auto-focus and data playback. Photodiodes E and F are used for autotracking.

Optical Design – Autotracking

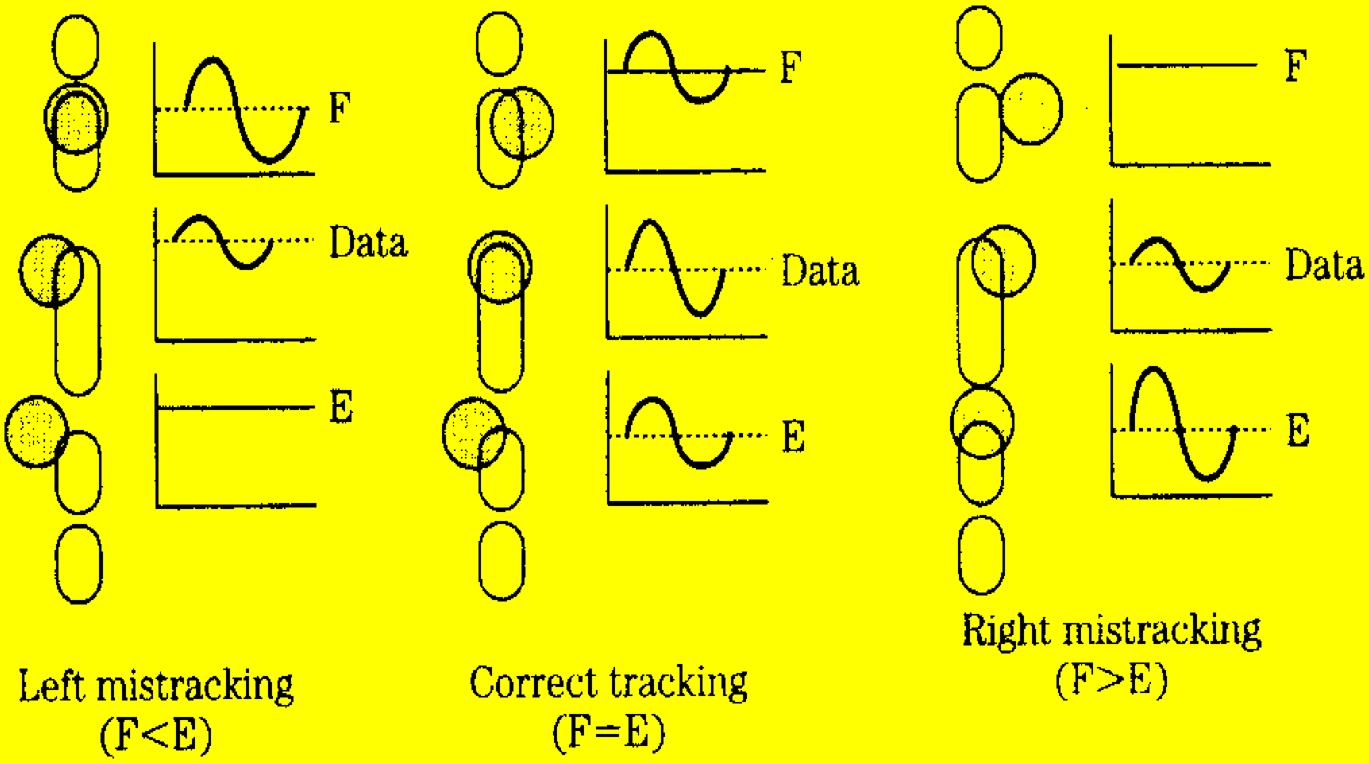
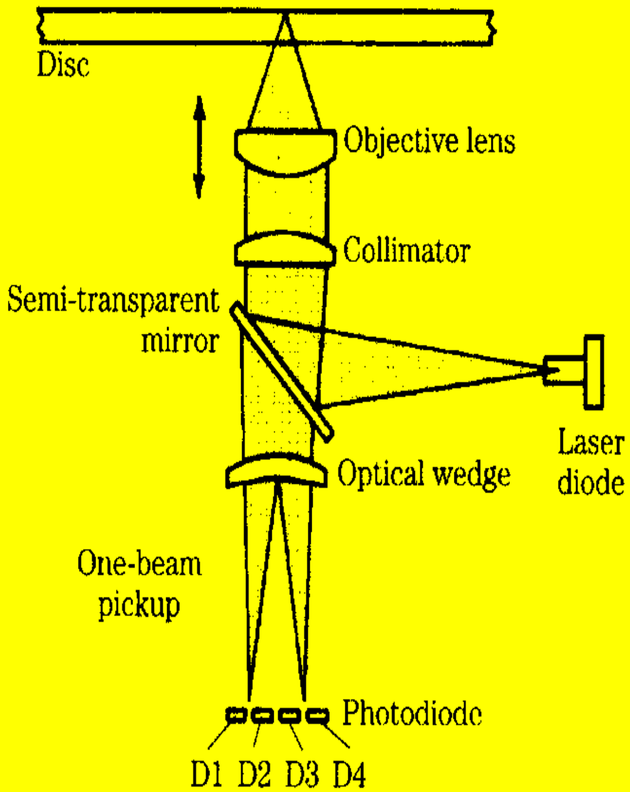
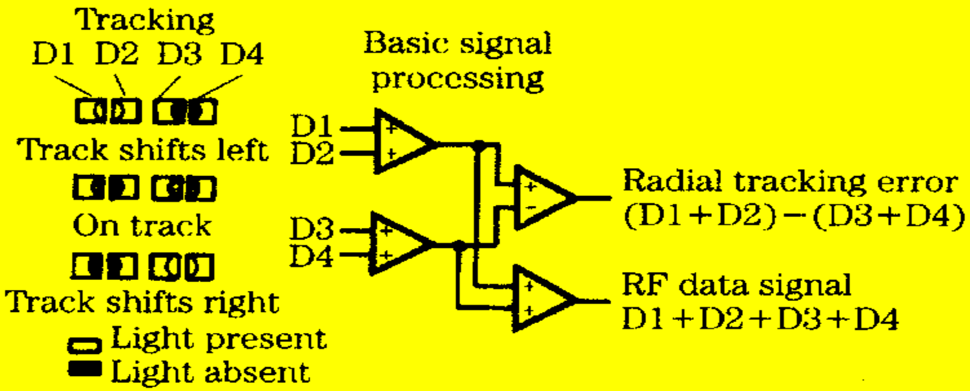


Figure 9.12 A tracking-correction signal is generated from an intensity imbalance in the two secondary beams. A servo system dynamically maintains tracking.

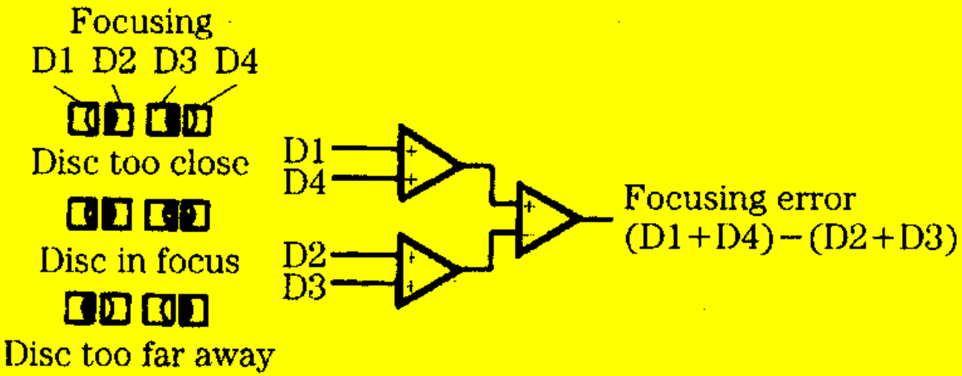
Optical Design – Autotracking



A The reflected beam is split by a wedge lens and directed to four photodiodes.



B Tracking is accomplished by intensity asymmetry in the beam.



C Focusing is maintained through the angle of deflection between the split beams.

Player Electrical Design

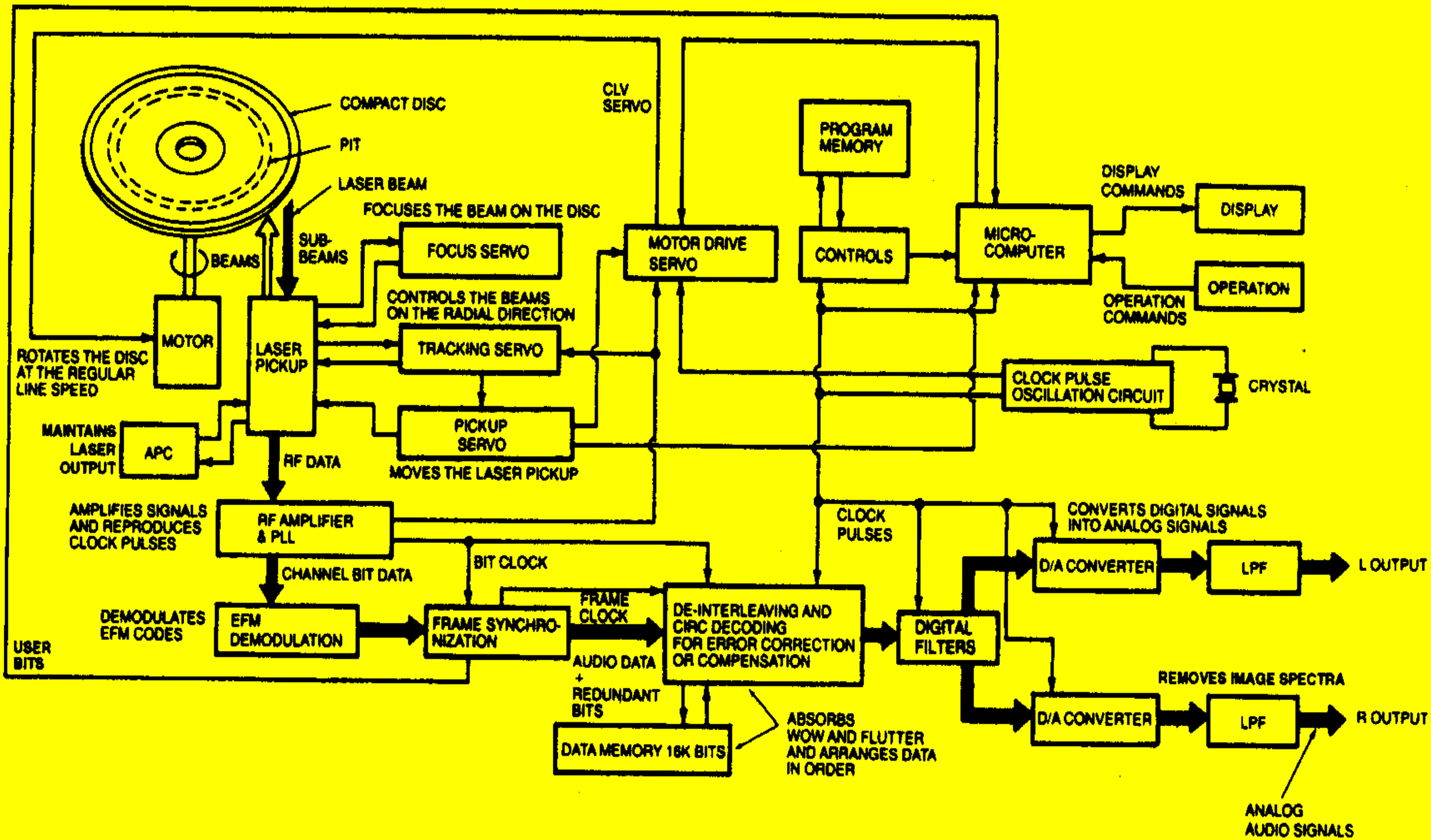


Figure 9.14 A CD player, showing optical processing and output signal processing.

EFM demodulation

- The **RF signal** from the disc contains all data, and is also used to maintain proper CLV rotation velocity of the disc.
- **3T** describes a **720 KHz** signal, and **11T** describes a **196 KHz** signal at 1.2 m/s. **T** refers to the period of 1 channel bit which is **464 ns**.
- A collection of EFM waveforms is called the **eye pattern.**
- Whenever a player is tracking data, the **quality** of the **signal** can be observed from the **pattern**.
- **Demodulation** : Eye pattern from disc → converted to NRZI → converted to NRZ → EFM data → audio data

Eye Pattern

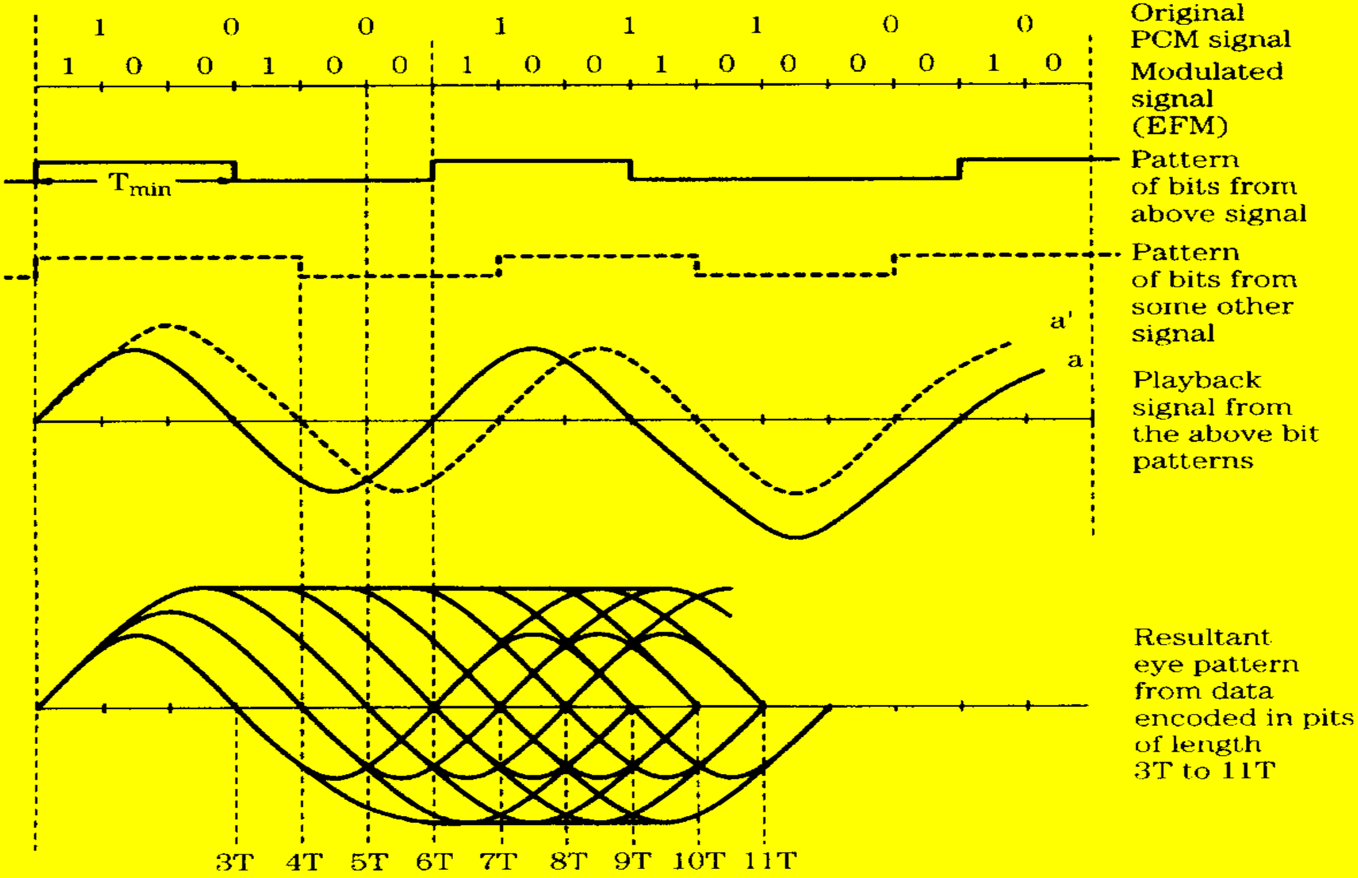


Figure 9.15 The modulated EFM data is read from the disc as an RF signal. The RF signal can be monitored through an eye pattern by simultaneously displaying successive waveform transitions.

EFM demodulation

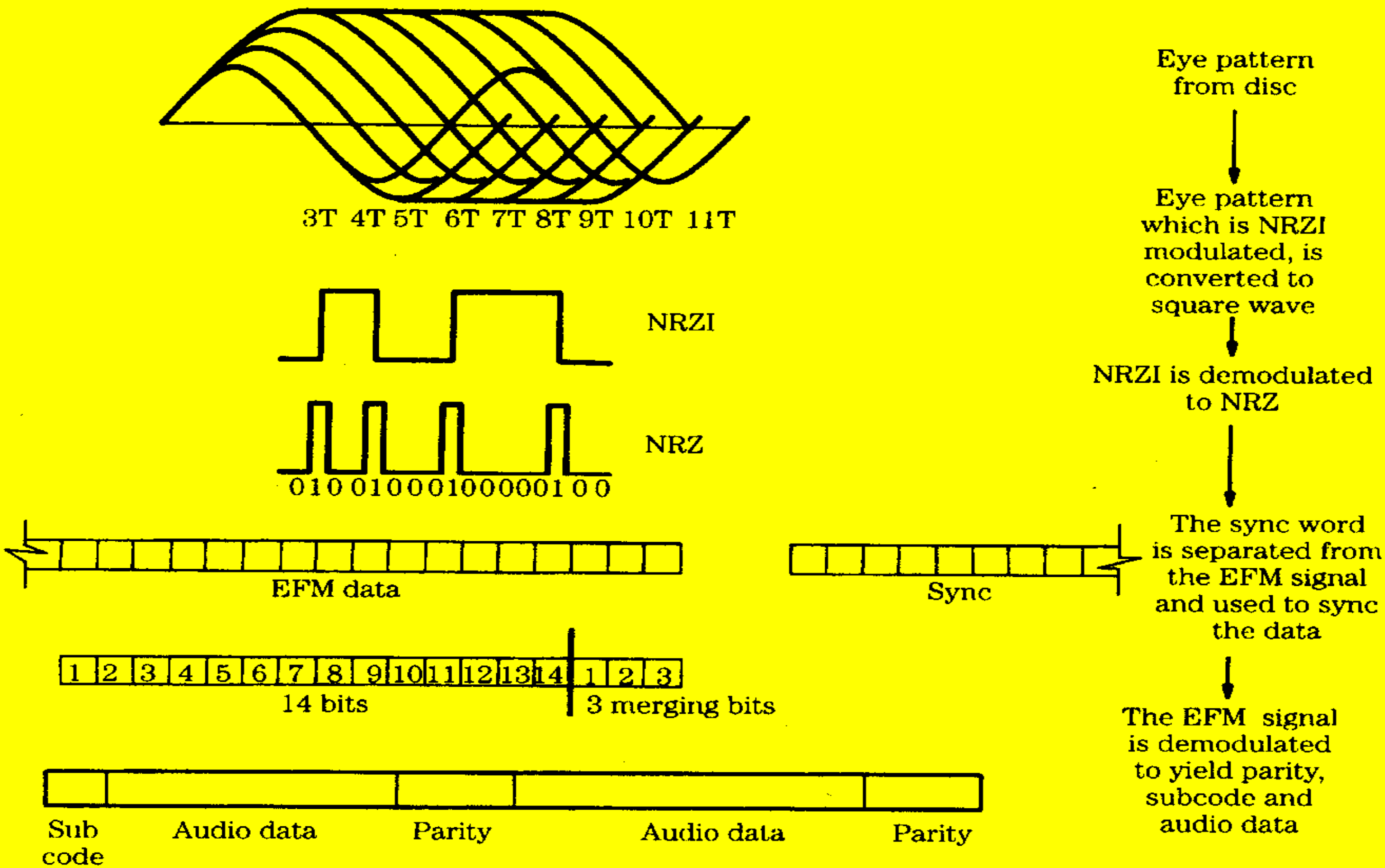


Figure 9.16 Demodulation of the output RF signal permits recovery of synchronization, subcode, audio, and error-correction data.

Error Detection and Correction

- Following demodulation, data is sent to a **Cross-Interleave Reed-Solomon code** circuit for error detection and correction. CIRC can enable complete correction of burst error up to **3874 bits** (a **2.5 mm** section of pit track).
- The raw-bit error rate (**BER**) on a disc is between $\mathbf{10^{-5}}$ and $\mathbf{10^{-6}}$. Following **CIRC error correction**, the bit error rate is reduced to $\mathbf{10^{-10}}$ to $\mathbf{10^{-11}}$.
- Data is corrected through two CIRC decoders, C1 and C2. The **C1 decoder** corrects minor errors and flags uncorrectable errors. The **C2 decoder** corrects larger errors and aided by the error flags.
- Most of the uncorrectable errors can be reconstructed by **linear interpolation** or undergone **concealment**.

Subcode

- Each frame contains **8** subcode bits, containing information describing where **track begins and ends**, **track number**, **disc time**, **index points**, and **other parameters**.
- Only the **P and Q** subcode bits are defined in the CD-Audio format.
- For a CD-audio, 44100 left and right 16-bit audio samples per second → the byte rate is 176.4 Kbytes/sec. With 24 audio symbols in each frame → the **frame rate** is **7350 Hz**.
- A subcode **block** is constructed sequentially from **98 successive frames**. The subcode block rate is **75 Hz**.

Subcode

- The **P** channel contains a **flag bit**. It designates the start of a track, as well as the lead-in and lead-out areas on a disc.
- The **music data** is denoted by **0** and the **start flag** as **1**. The length of a start flag is a minimum of **two seconds**.
- Lead-in and lead-out signals tell the player where the music program begins and ends.
- **Lead-in** contains signal consists of **all 0s**. At the end of the lead-in, a start flag two to three seconds long appears just prior to the start of music.
- During the last music track, preceding the lead-out, a start flag of two to three seconds appears. The end of that flag designates the start of **lead-out**. Following that time, a signal consisting of **alternating 1s and 0s** (at a 2-Hz rate) appears.

Subcode

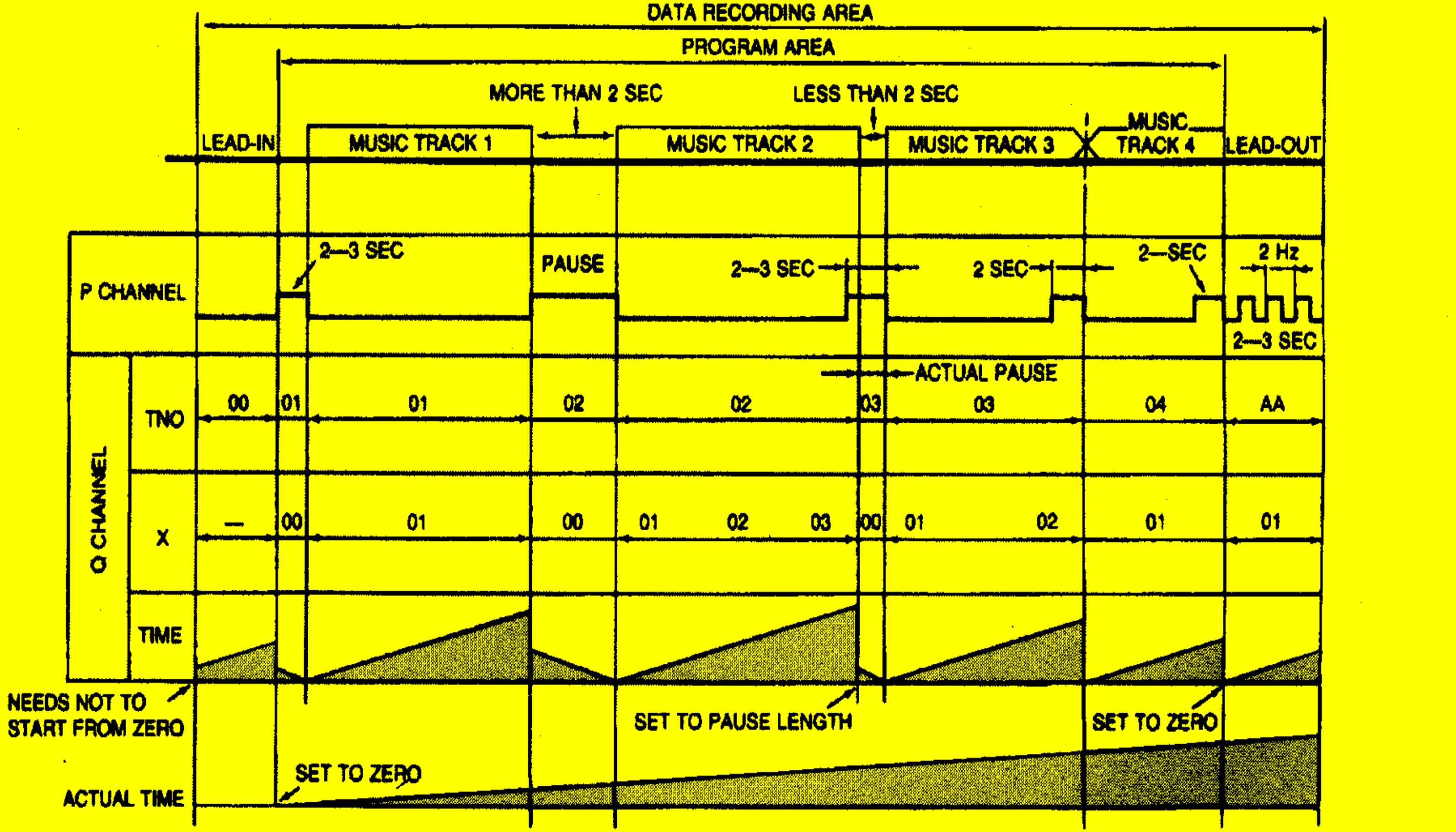


Figure 9.18 An example of the program information contained in the P and Q subcode channels across a disc surface.

Subcode

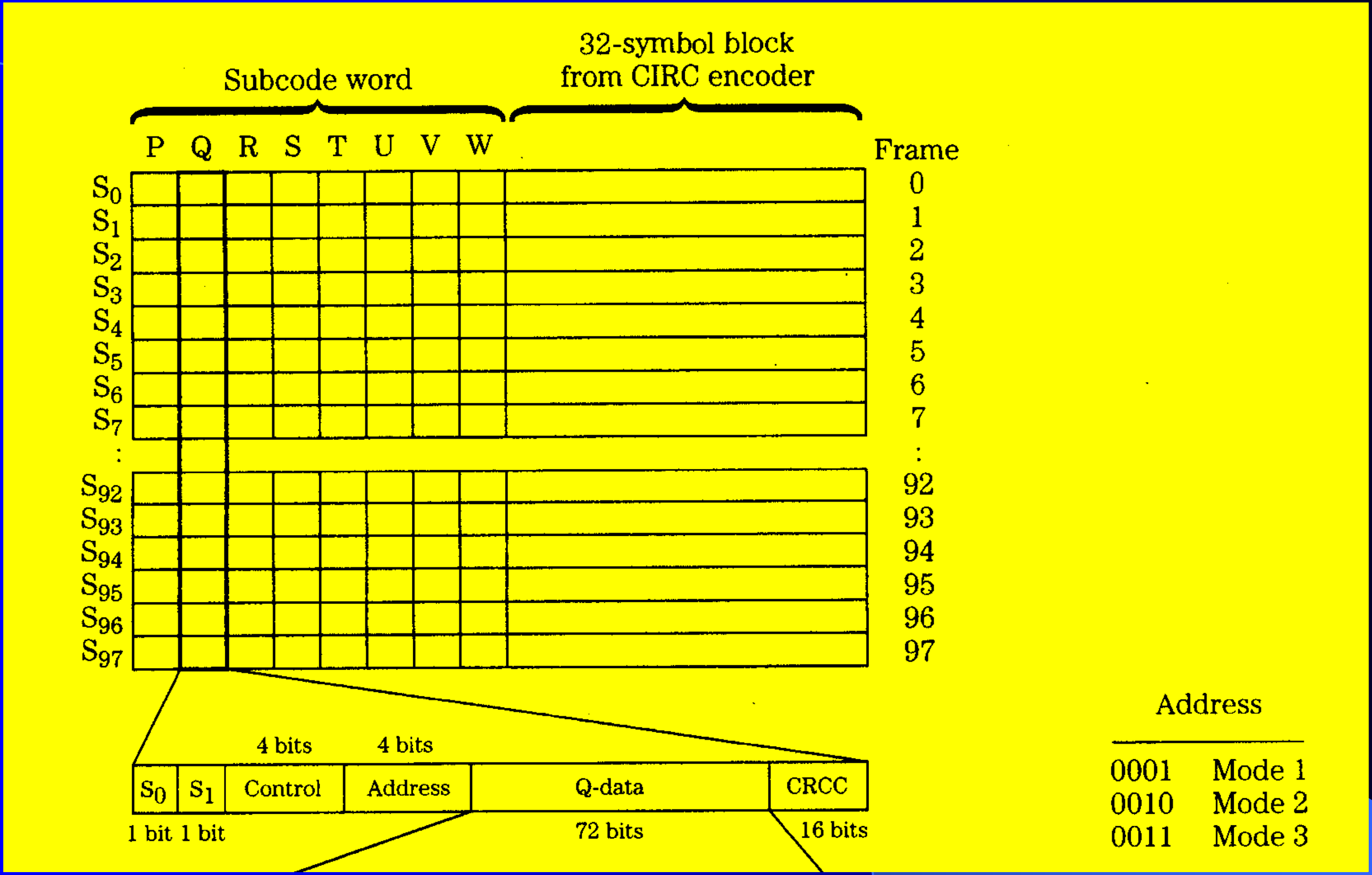
- The **Q** channel contains four information : **control**, **address**, **Q data**, and an **error detection code**.
- Control (4-bits) : 1 - number of channels, 2 - audio/data content, 3 - digital copy and 4 - pre-emphasis.
- Address (4 bits) : **mode1** (number and start times of tracks), **mode2** (catalog number), **mode3** (ISRC code).
- Q data (72 bits):

  Mode1 : **information** in the disc **lead-in area**, **program area**, and **lead-out area**.

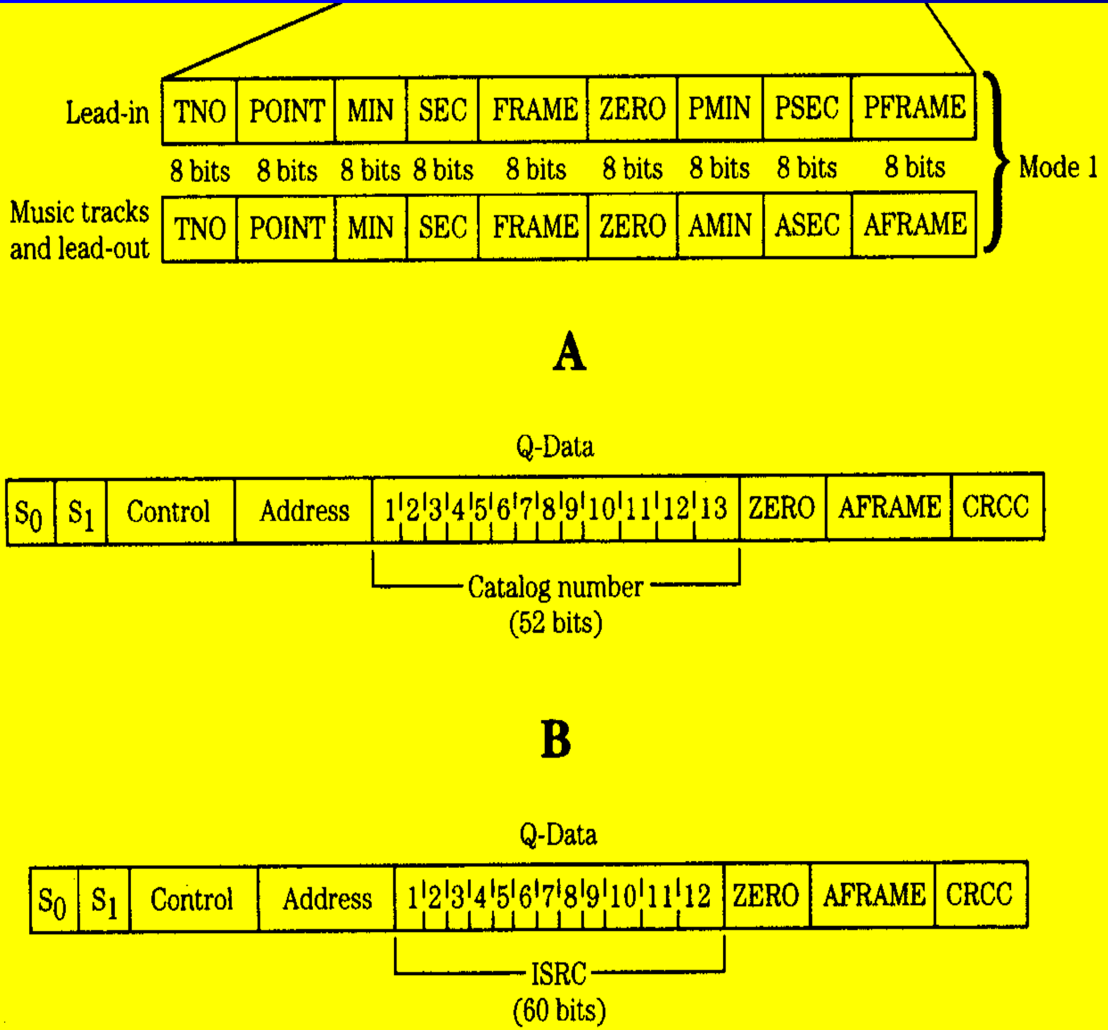
  Mode2 : **catalog number** of the disc such as **UPC/EAN** – Universal Product Code / European Article Number.

  Mode3 : **ISRC number** for each track including country code, owner code, year of recording, and serial number.

Subcode


32-symbol block
from CIRC encoder
Subcode word
P Q R S T U V W
Frame
S_0 S_1 S_2 S_3 S_4 S_5 S_6 S_7
S_{92} S_{93} S_{94} S_{95} S_{96} S_{97}
0 1 2 3 4 5 6 7
92 93 94 95 96 97
4 bits
4 bits
S_0
S_1
Control
Address
Q-data
CRCC
1 bit 1 bit
72 bits
16 bits
Address
0001 Mode 1
0010 Mode 2
0011 Mode 3

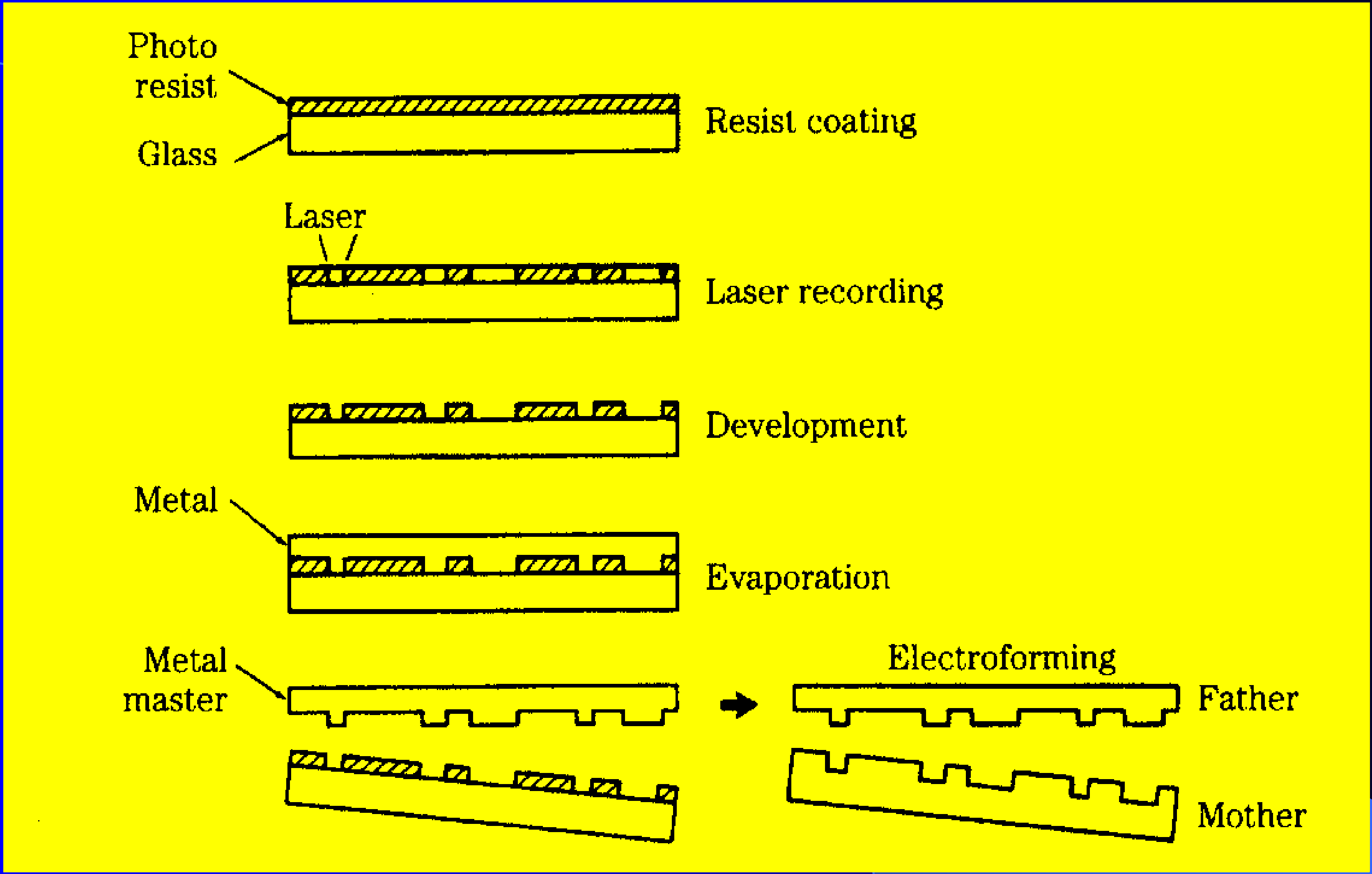
Subcode



Control

Bit number	Denotes
1=0	2 channel
1=1	4 channel
2=0	Audio content
2=1	Data content
3=0	Copy prohibited
3=1	Copy permitted
4=0	Pre-emphasis off
4=1	Pre-emphasis on

Disc Manufacturing - Mastering



Disc Manufacturing - Replication

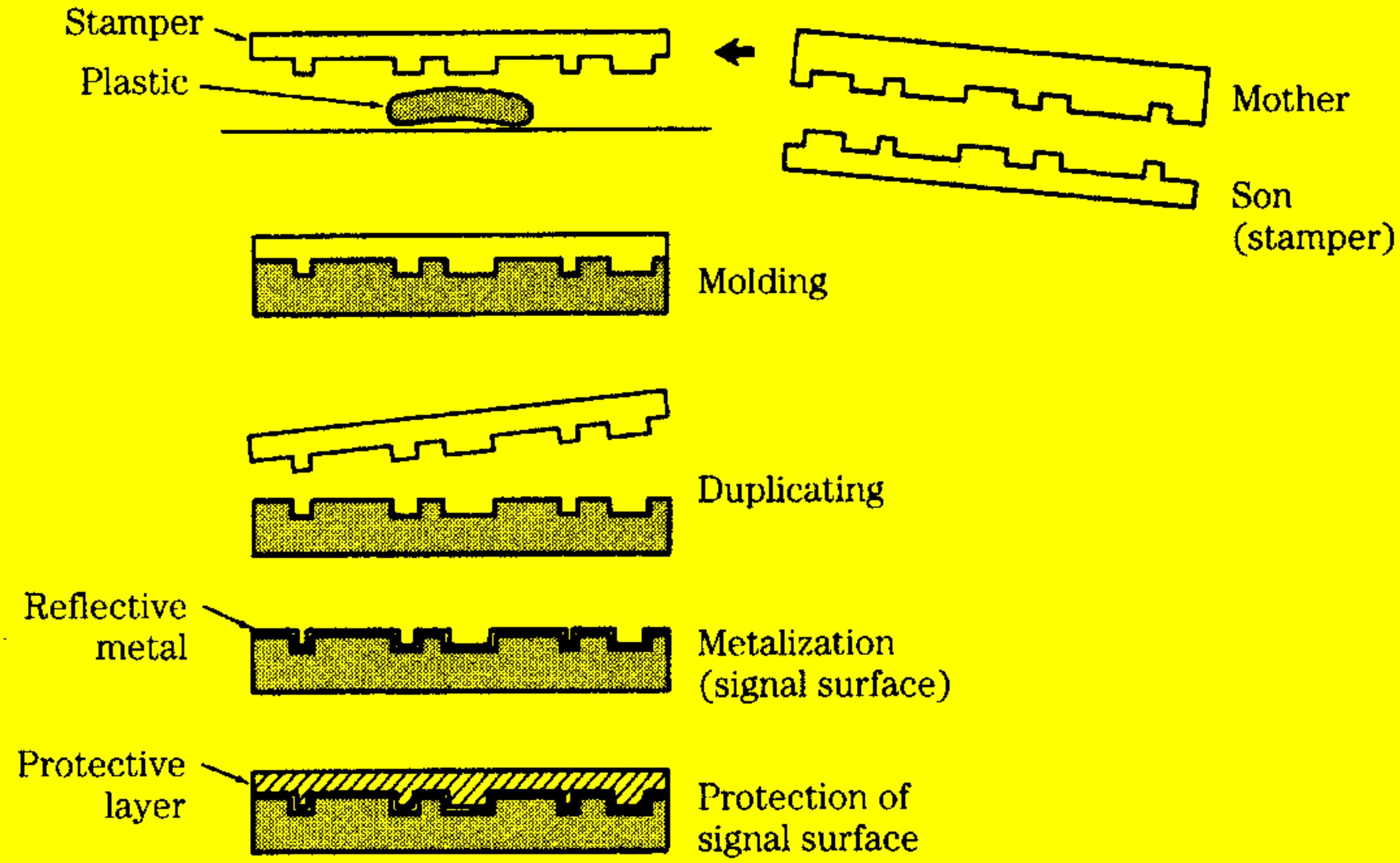


Figure 9.19 A summary of the principal steps in the CD disc manufacturing process.

Mastering

- The **laser beam recorder (LBR)** uses a **15-mW**, **460-nm** wavelength, **argon gas laser**, with **NA of 0.9**. Another laser which does not affect the photoresist is used for focusing and tracking.
- **Developing** fluid washes the rotating disc surface, etching away the exposed areas of photoresist.
- Pit depth (¼ of 780nm, divided by the refractive index of 1.55) is **theoretically 126 nm**.
- In practice, a compromise must be made to **balance** the need for **zero reflected pit light** against that conducive for **signal tracking**, which requires a 1/8 wavelength pit depth. A production pit depth of **110 nm** is typical.

Disc replication

- A **polycarbonate** material is used, because of its **low vapor absorption coefficient**, about 70% less than that of PMMA.
- CD **birefringence** is specified to be less than **100 nm**.
- After molding, a layer of Al, Ag or Au (about **50-100 nm** thick) is placed over the pit surface. The reflectivity is specified to be at least **70%.**
- The metal layer is covered by an **acrylic layer** to protect the metal layer from scratched and oxidation.

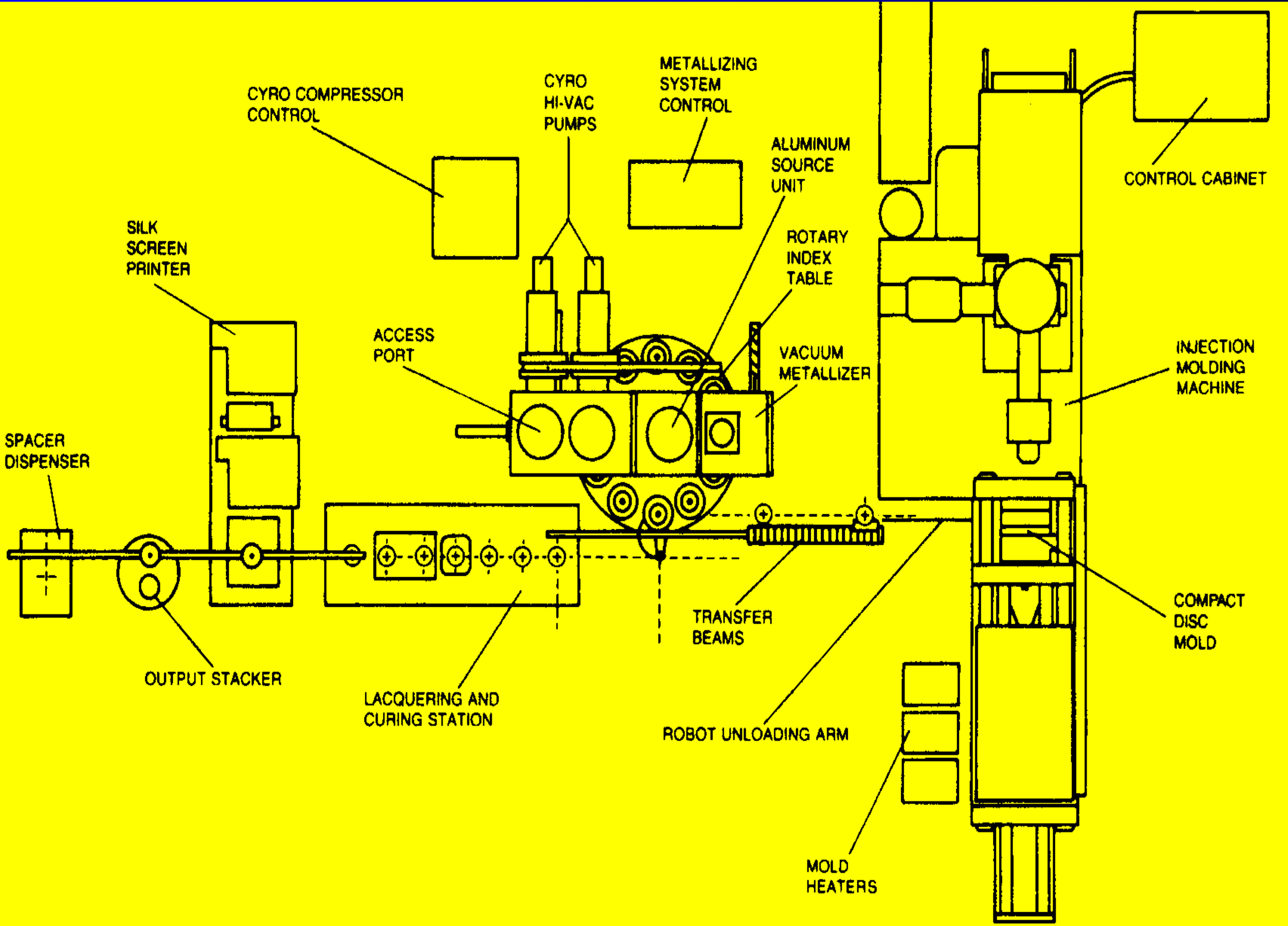


Figure 9.20 An example of the in-line hardware used to manufacture compact discs. Critical processes are enclosed in small clean enclosures. (*Musitech*)

Mechanical & Optical Properties

- **Retardation** (**Birefringence**) : **+/- 100 nm**
  - High BLER, Low Carrier/Noise Ratio & Optical readout
- **Radial deviation** : **+/- 1.6**
  - Loss of the HF signal & High Jitter Value
- **Tangential Deviation** : **+/- 0.6**
  - Loss of the HF signal & High Jitter Value
- **Axial Deflection** : **+/- 500 mm**
  - Focusing problem, Loss of the HF signal, High BLER & E32
- **Axial acceleration** : **+/- 10 m/s^2**
  - Affect tracking performance & stability of focus servo system.

Mechanical & Optical Properties

- **Birefringence**

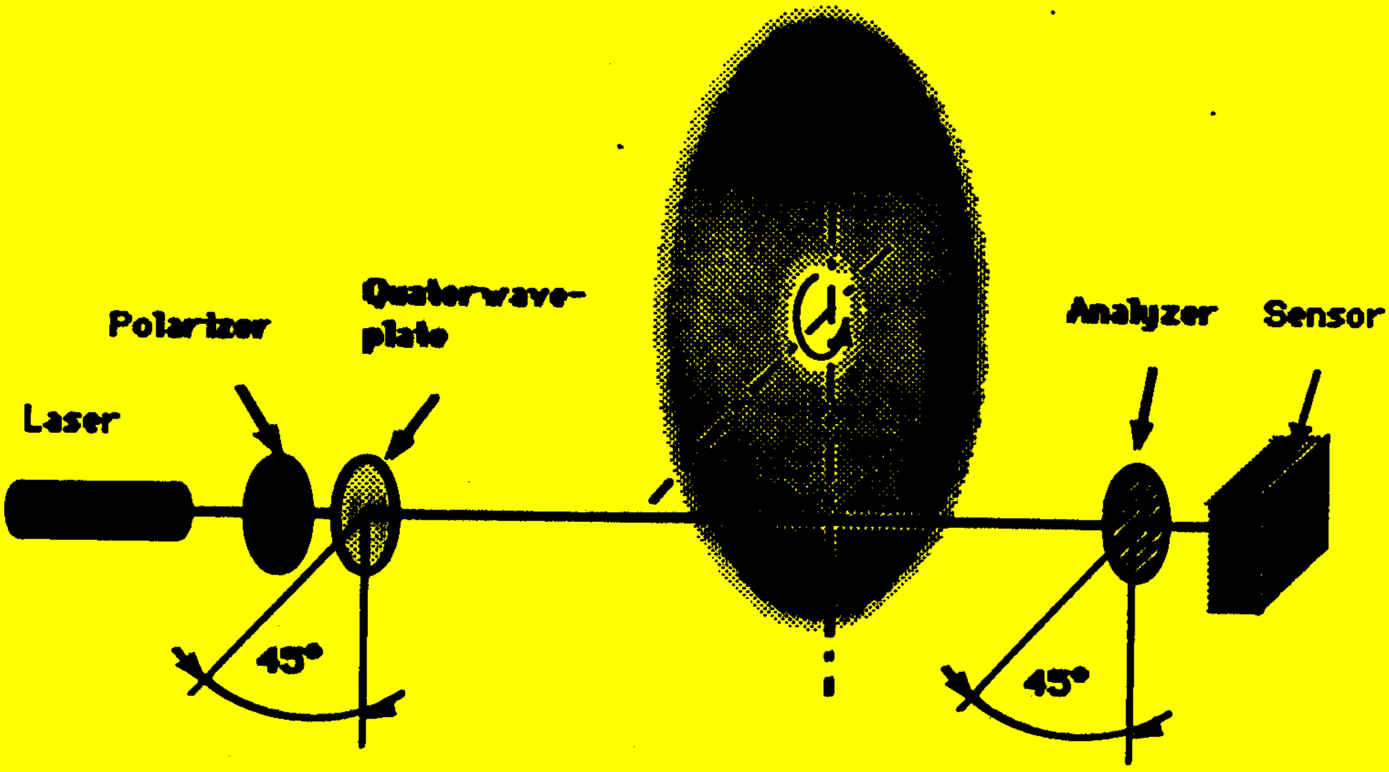


Fig. 1: **Principal optical arrangement for the inspection of birefringence**

Mechanical & Optical Properties

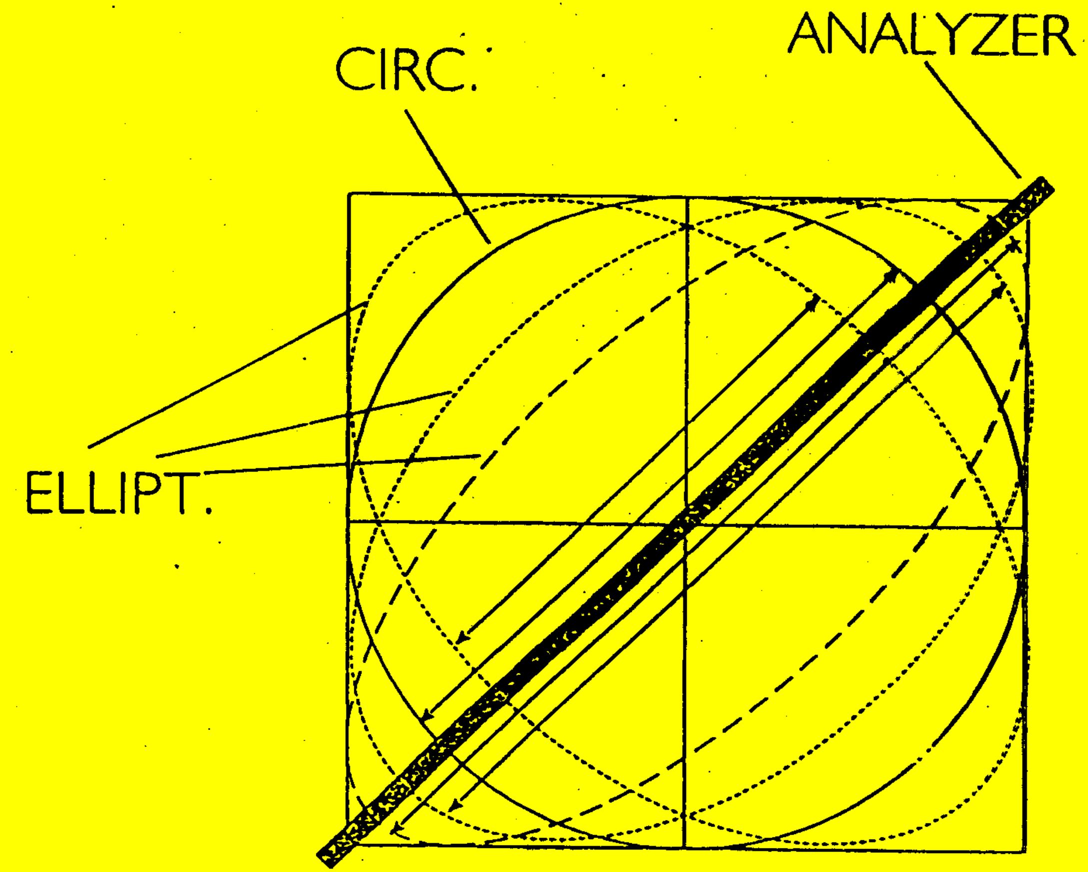
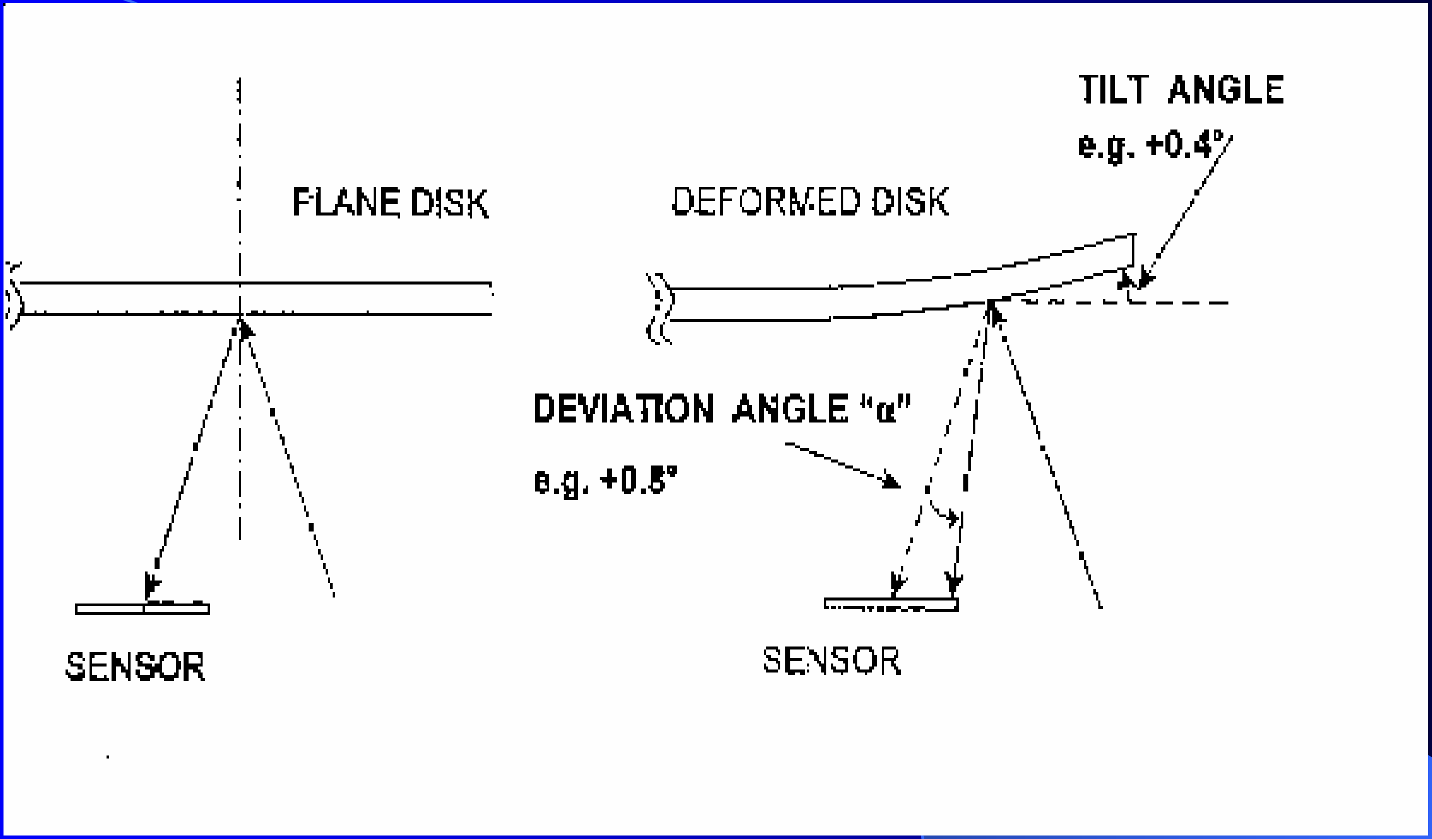
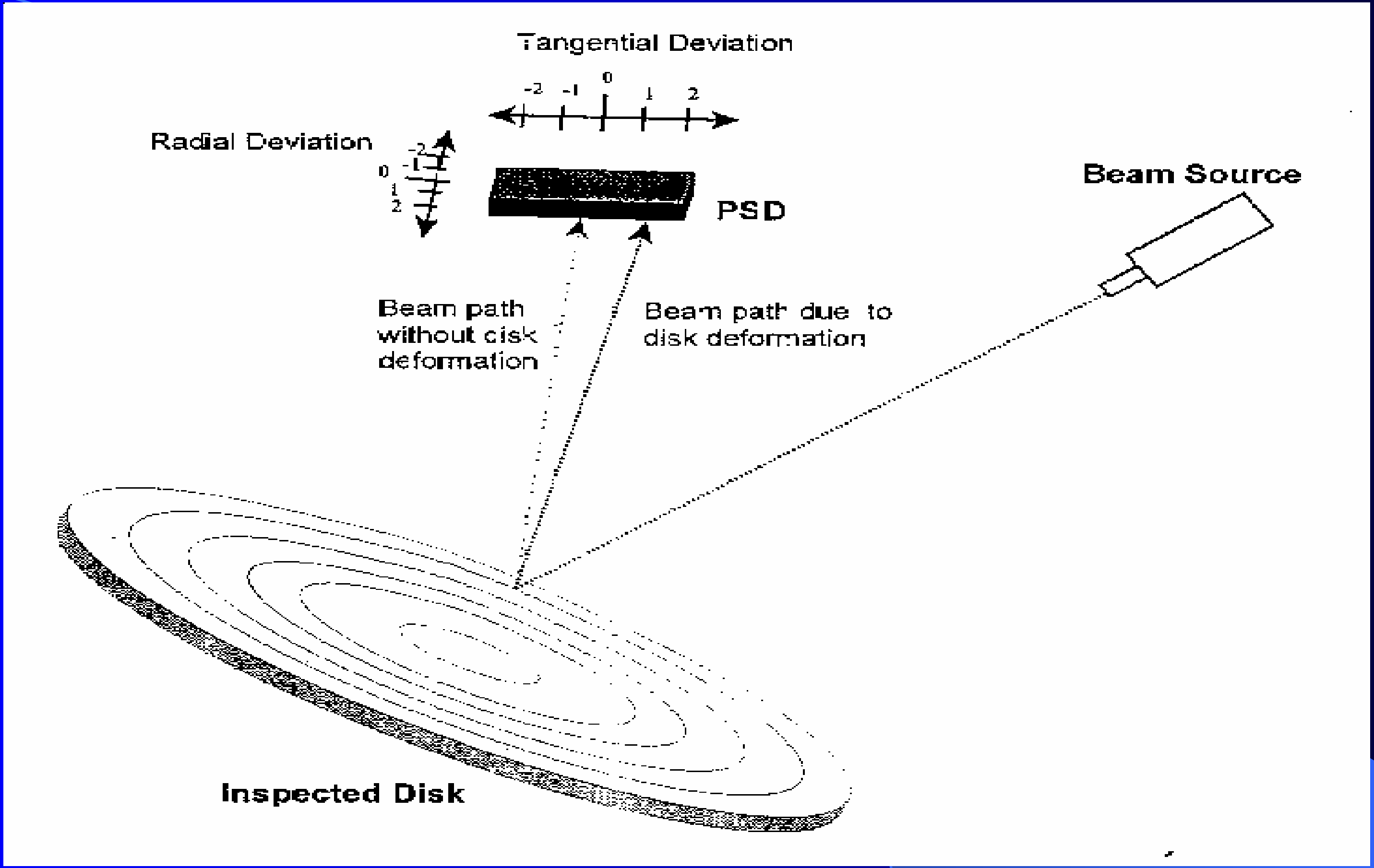


Fig. 3.1: Birefringence Measurement Principle

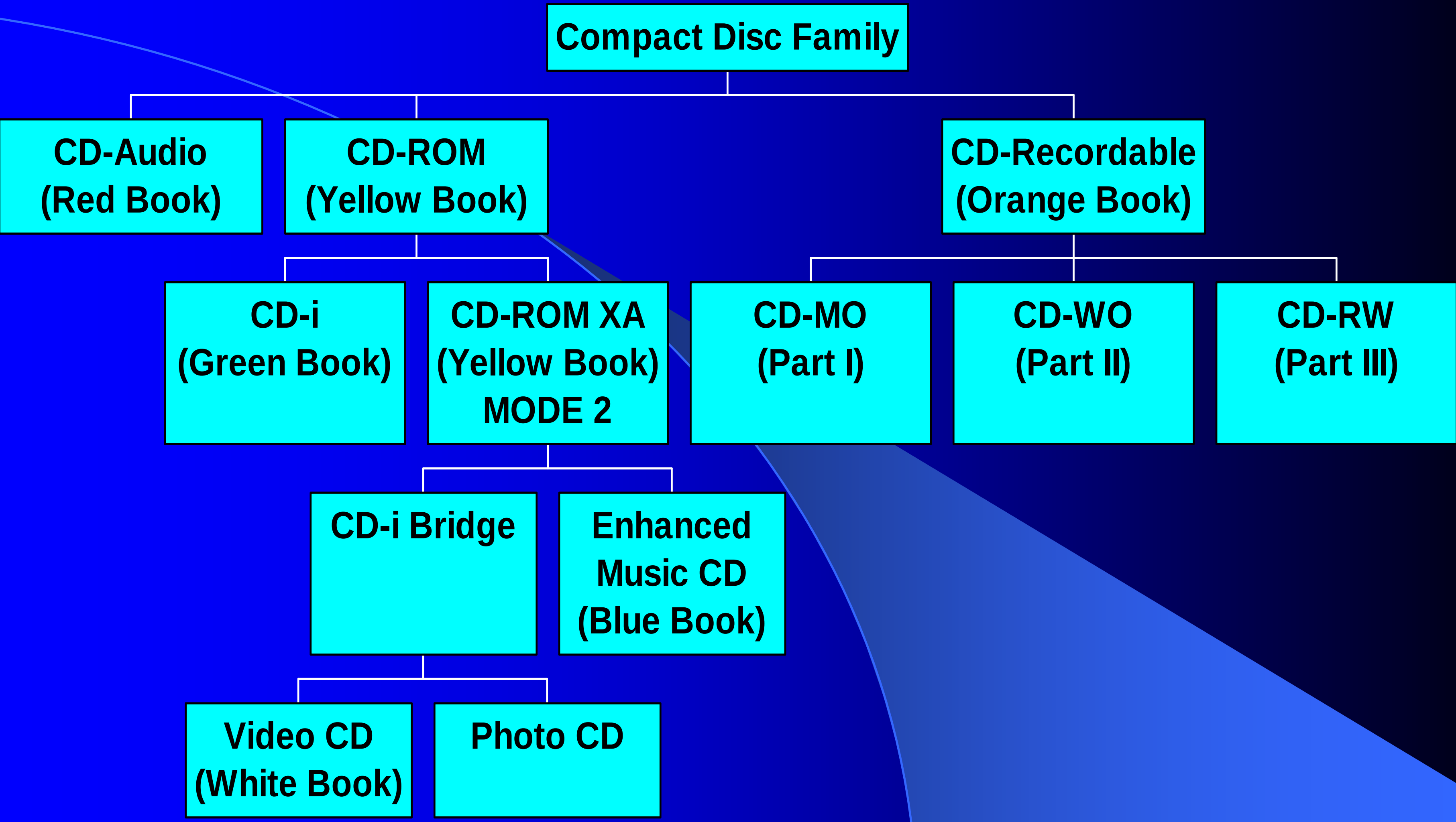
Mechanical & Optical Properties



Mechanical & Optical Properties



Alternative CD formats



CD-ROM

- The CD-ROM standard, sometimes called the **Yellow Book** was introduced in 1983.
- **98** CD frames are summed to form a data block **2352** bytes (24 byte x 98) in length.
- A mode 1 CD-ROM holds **682 MB** of user information (**333000 blocks** X 2048 bytes).
- **Mode 1** : **2048 bytes** of each block to user data; **288** bytes are given to extended **error detection** and **correction.**
- **Mode 2** : **2336 bytes** to be used for user data.
- **Mode 1** thus has two independent layers of error correction (**EDC+ECC and CIRC**) whereas **Mode 2** uses only **CIRC** coding.

CD-ROM

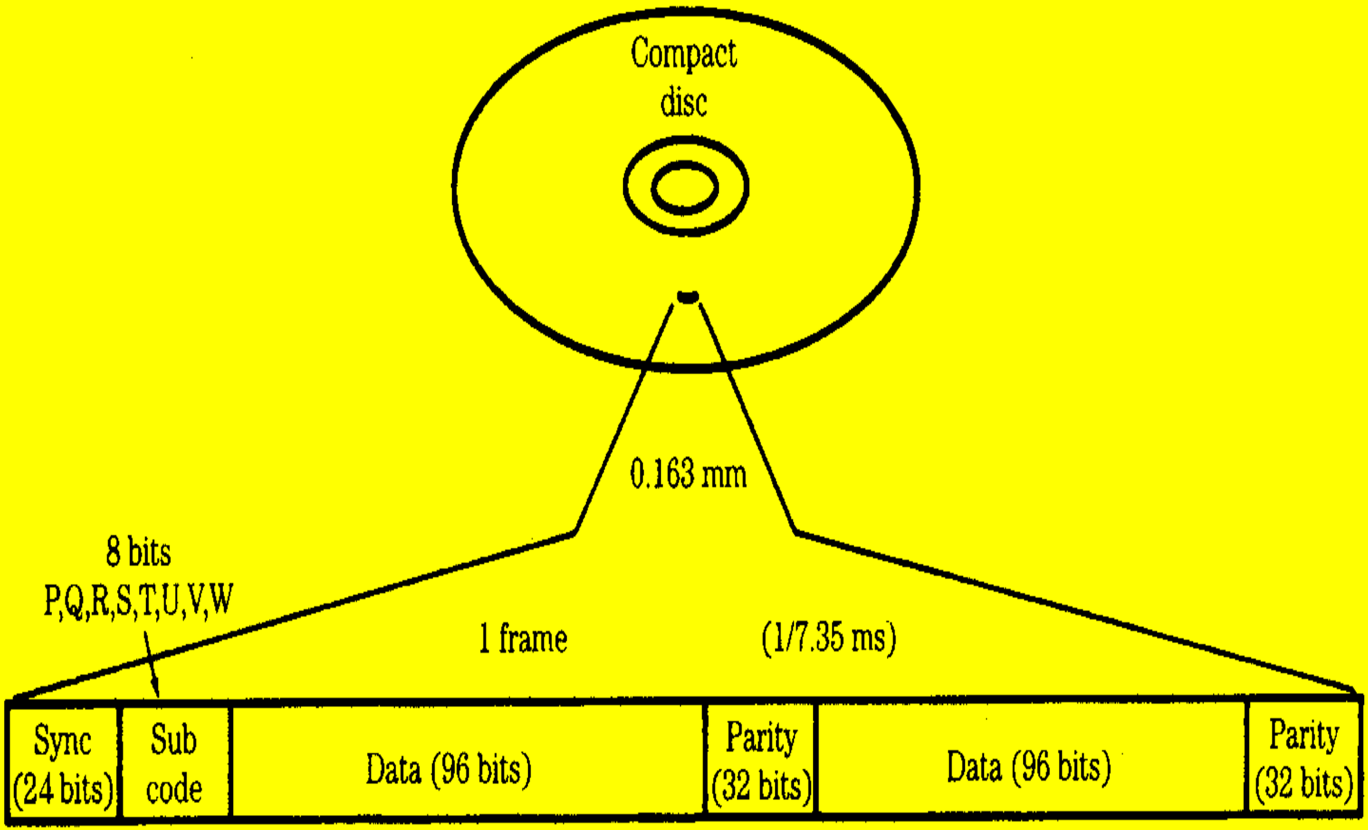


Figure 9.4 Elements of a CD frame shown without EFM modulation and interleaving. All data except the sync word undergo EFM modulation to create a total of 588 channel bits.

CD-ROM

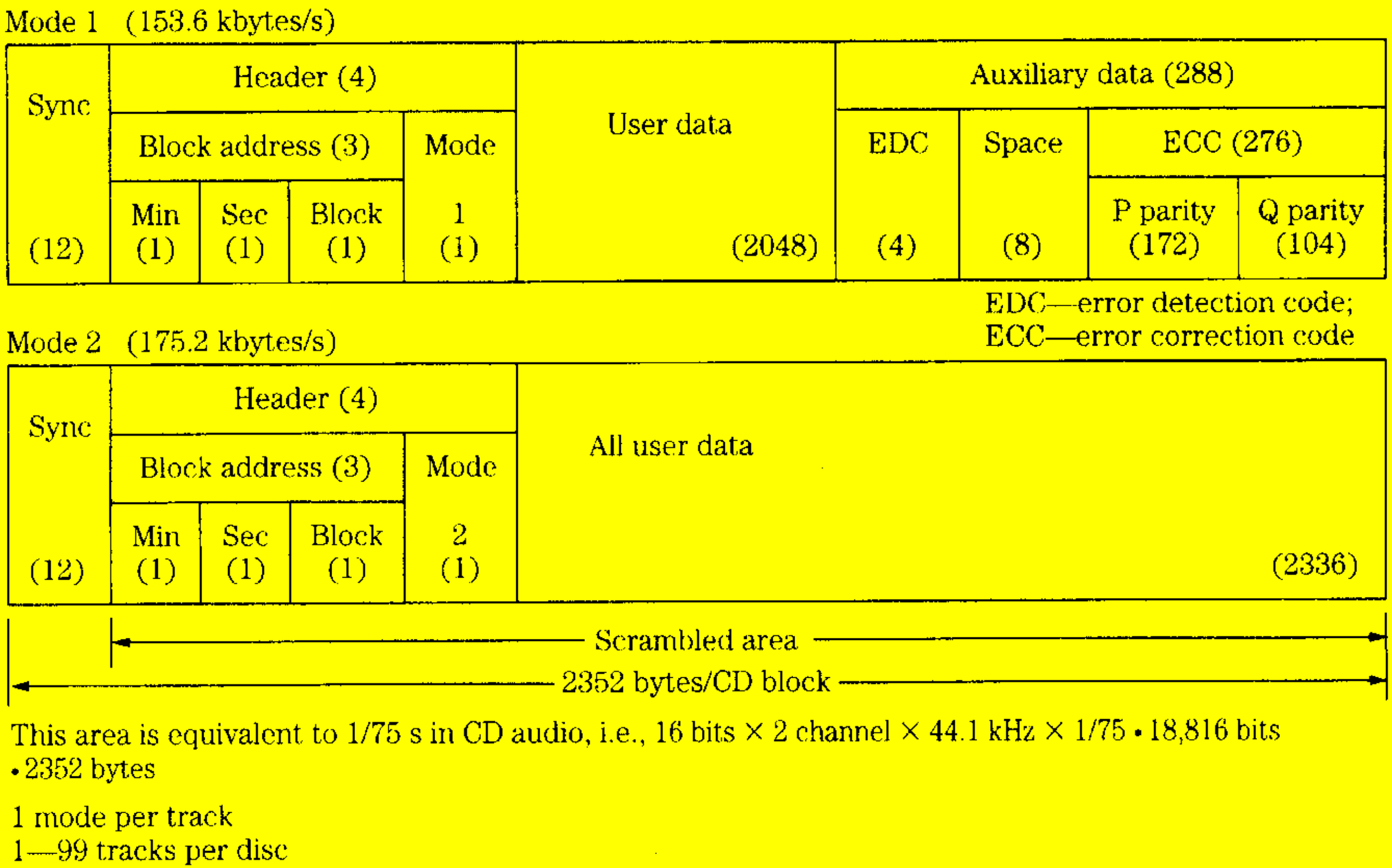


Figure 9.22 The CD-ROM specification contains two modes of data block structures. Mode 1 allows for extended error detection and correction, and Mode 2 provides capacity for additional user data.

CD-ROM/XA

- CD-ROM/XA (**eXtended Architecture**) is an extension to Mode 2 standard. **Computer data**, **compressed audio data**, and **video and picture data** can all be contained on one XA track.
- CD-ROM/XA Mode 2 provides a **sub-header** that defines the block type.
- **Form 1** for **computer data**, provides a **2048**-byte user area.
- **Form 2** for **compressed audio/video data**, provides **2324** bytes.
- CD-DA Red Book data cannot be placed on a XA track.
- The CD-ROM/XA format is defined in the **White Book**.
- The **Video CD** and **Photo CD** are types of CD-ROM/XA.

CD-ROM/XA

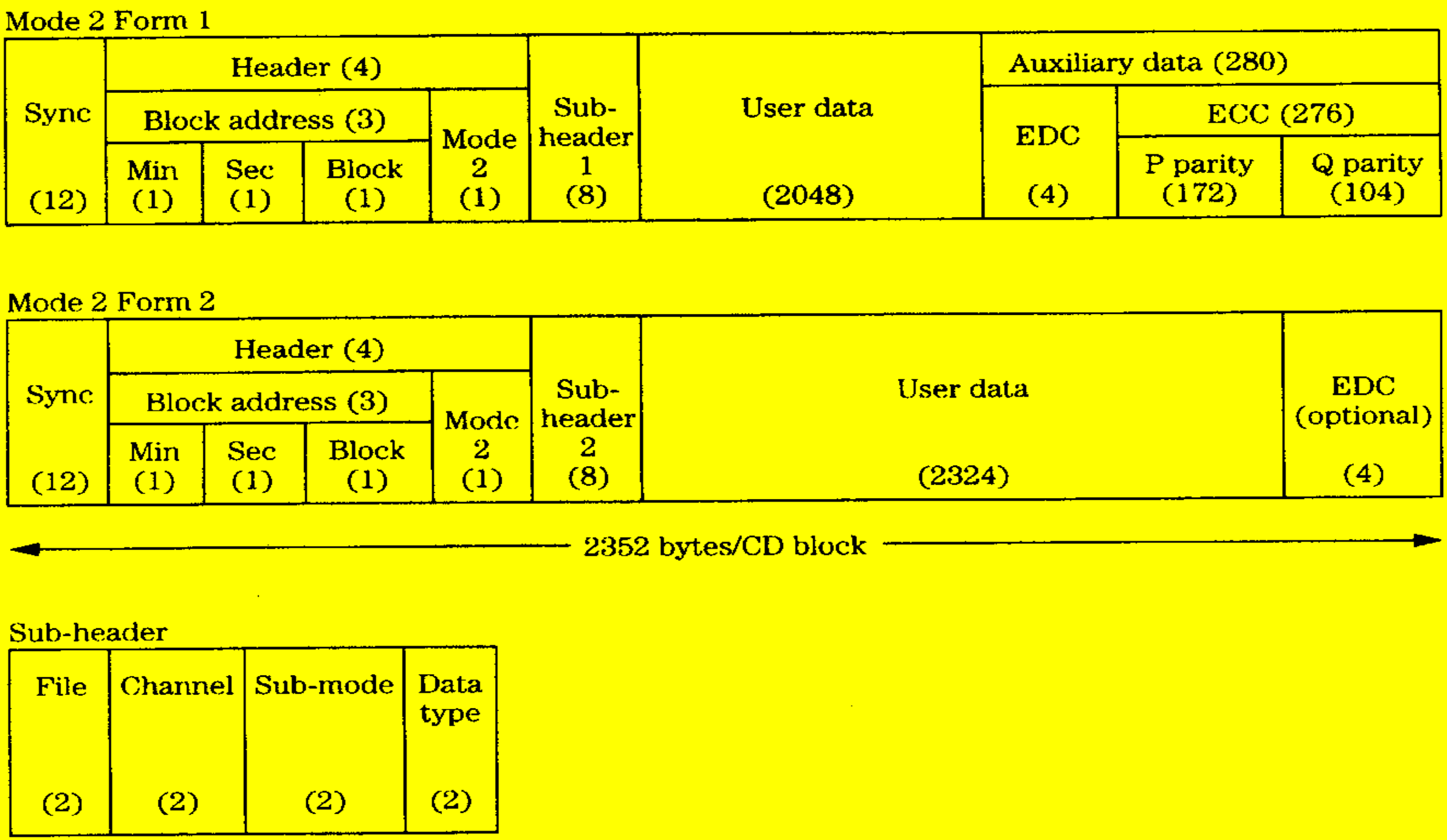


Figure 9.23 The CD-ROM/XA data format is based on the CD-ROM Mode 2 format. It provides two forms: extended error detection and correction, or increased user data capacity. These structures also apply to CD-i and Bridge discs.

Hybrid audio/data CD

- Hybrid audio/data CD formats (**CD Extra**, Stamped Multi-session or **Mixed Mode**) combine several different format types (such as CD-DA and CD-ROM/XA) on a single disc.
- A **CD Extra** disc has **audio data** in the first session, with **ROM-XA mode 2 data** in the second session.
- **CD Extra** is described in the **Blue Book**.
- CD Extra discs must contain the **AUTORUN.INF** file as well as **CDPLUS** and **PICTURES** folder.
- In **Mixed Mode** CDs, **ROM data** is placed in **track 1**, while CD-Audio data is placed in subsequent tracks.
- To avoid an audio player accesses the ROM track, a "**pre-gap**" may be used such that ROM data is "hidden" by placing it after the disc TOC, but before the audio track.

Compact Disc Interactive (CD-i)

- CD-i is a **multimedia** extension of CD-ROM.
- CD-i specified in the **Green Book**, defines how various types of information (Ex. Video, audio, text, and graphic) are identified on the media.
- The CD-i data format is derived from the **CD-ROM Mode 2** format and is arranged in 2352-byte block.
- **Form 1** is used for **test**, **computer software**, and **compressed visual data**. **Form 2** is used for **real time audio and video**.
- The CD-i format provides **five levels** of audio quality.

  (1) 16-bit PCM (2) Hi-Fi A level (8-bit/37.8 kHz) (3) Mid-Fi B level (4-bit/37.8 kHz) (4) Speech C level (4-biy/18.9 kHz)

  (5) text-to-speech mode (MPEG-1 audio data reduction)

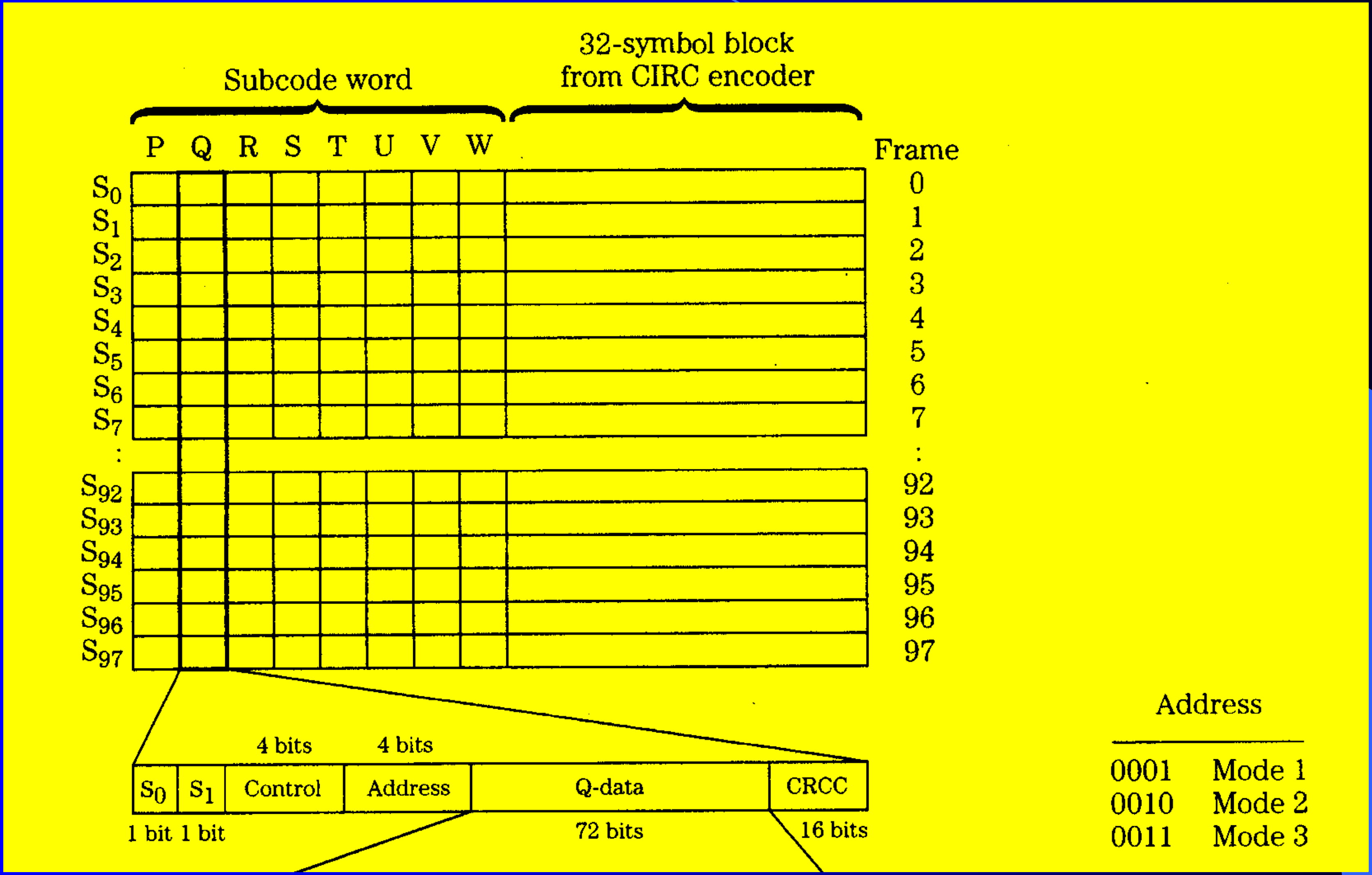
Photo CD

- The photo CD uses **digital imaging technology** to store, manipulate, and display **photographic pictures**.
- A full-resolution image with 2048 lines by 3072 pixels by 24-bit coding would require 18 MB of storage.
- The Photo CD system uses **data compression** and **decomposition** of the image signal to increase storage efficiency and decrease data transfer time.
- During authoring, high resolution image files are subjected to **4:1 data reduction**.
- Data decomposition : data placed in a low-resolution file is omitted from a medium-resolution file, which in turn is omitted from a high-resolution file.
- **Base image** consists of 512 lines of 768 pixels; it is used to produce images on consumer TV.

CD+G and CD+MIDI

- The CD+G and CD+MIDI formats encode graphics or MIDI software on CDs, in addition to regular audio data.
- Subcode synchronization occupies the first two frames, thus a subcode block contains 8 channels with 96 data bit. This data block is called a packet, and each quarter of a packet is called a pack.
- Only P and Q are reserved for audio control information. Over the length of a CD, the remaining channels, R to W, provide about 25 MB of 8-bit data.
- In CD+G discs, data is collected over thousands of CD frames to form video images or other data file.
- CD+MIDI format allows MIDI data stream to be stored, and output synchronously with the audio playback.

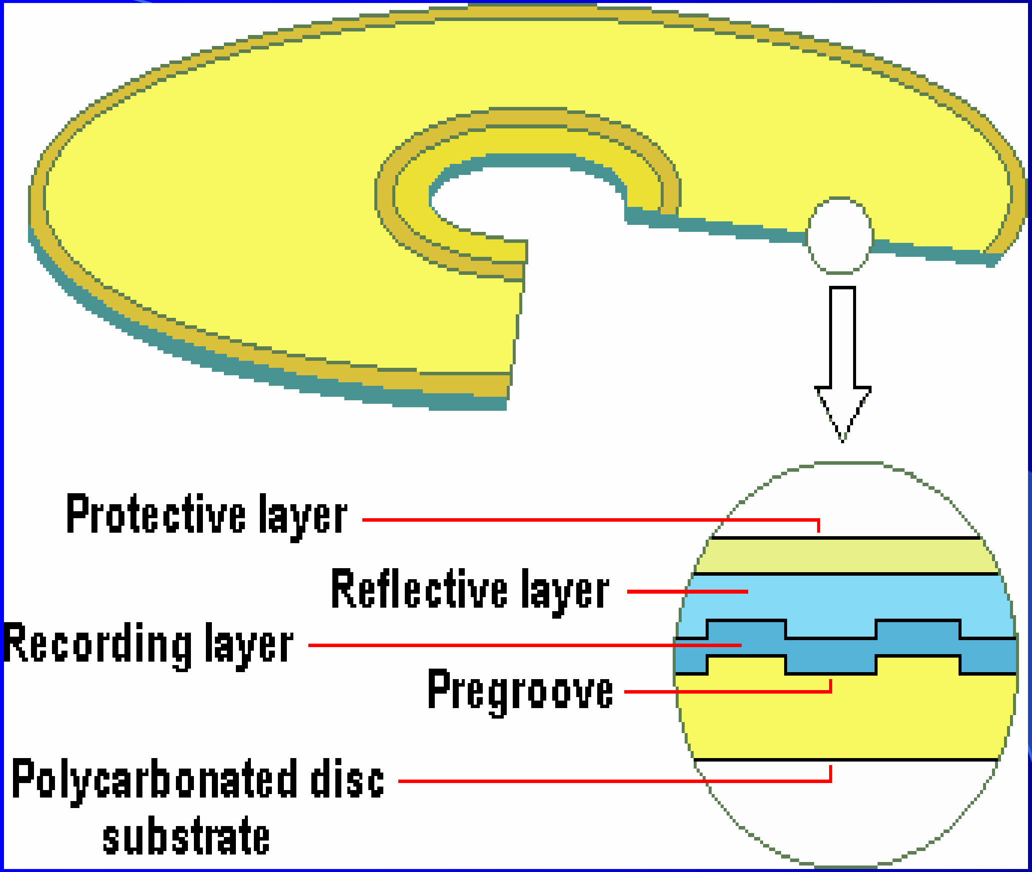
Subcode


32-symbol block
from CIRC encoder
Subcode word
P Q R S T U V W
Frame
S0 S1 S2 S3 S4 S5 S6 S7
S92 S93 S94 S95 S96 S97
0 1 2 3 4 5 6 7
92 93 94 95 96 97
4 bits
4 bits
S0
S1
Control
Address
Q-data
CRCC
1 bit 1 bit
72 bits
16 bits
Address
0001 Mode 1
0010 Mode 2
0011 Mode 3

CD-3 and Video CD

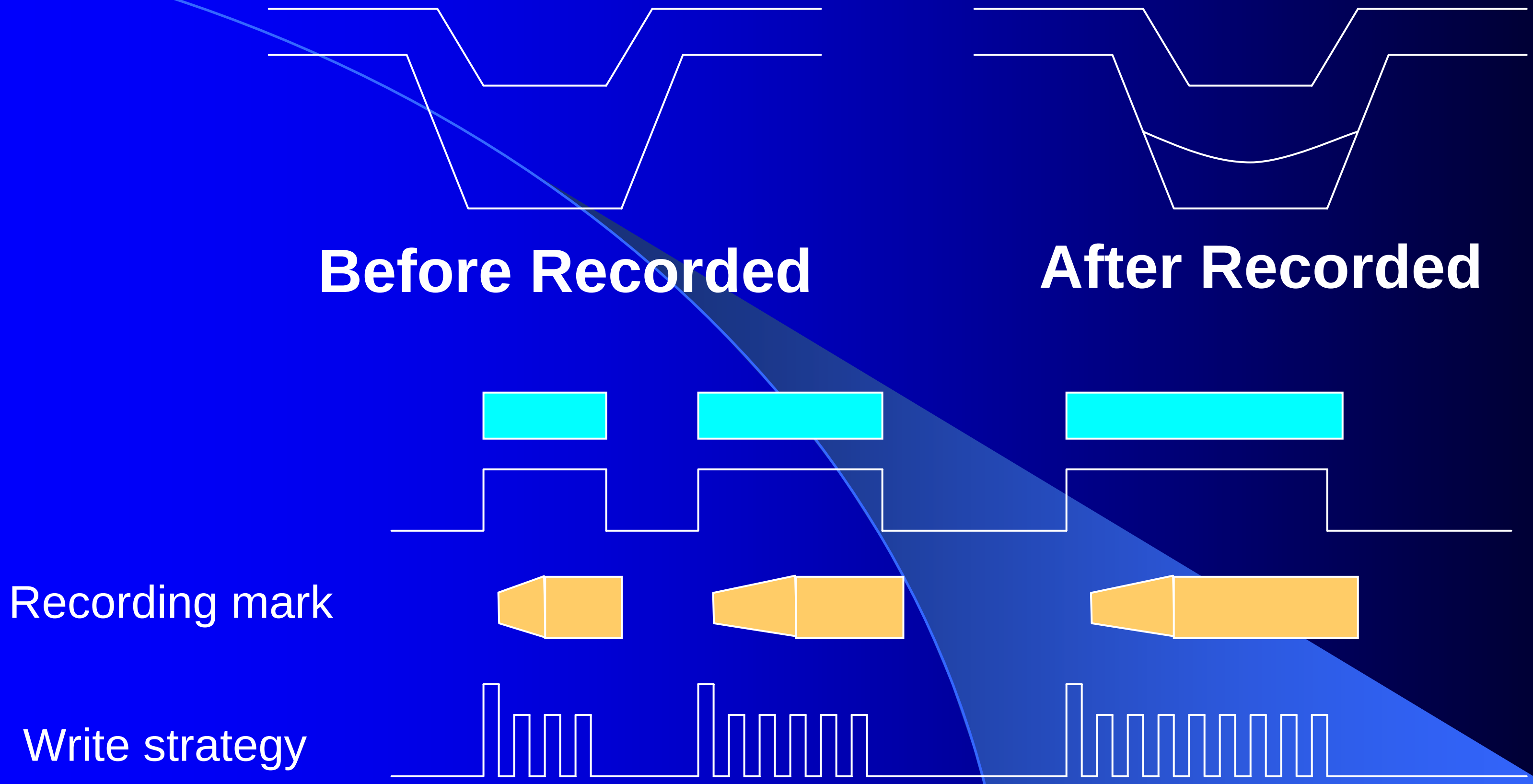
- The CD-3 format describes **80-mm** diameter discs that hold a maximum of **20 min.** of music or over **200 MB** of CD-ROM data.
- The video-CD format uses the **MPEG-1** coding standard for audio and video. It is described in the **White Book**.
- The audio signal is coded with the **Layer II** standard at 44.1 kHz.
- The video decoder chip permits full-motion video to be shown at either 29.97 (NTSC) or 25 (PAL/AECAM) frames per second at 352 pixels by 240 lines and 352 pixels by 288 lines respectively.
- Video bit rate is 1.15 Mbps and audio bit rate is 0.22 Mbps.

Process for CD-R



- Mastering
- Injection Molding
- Dye Coating
- Au/Ag Sputtering
- Lacquering
- Printing

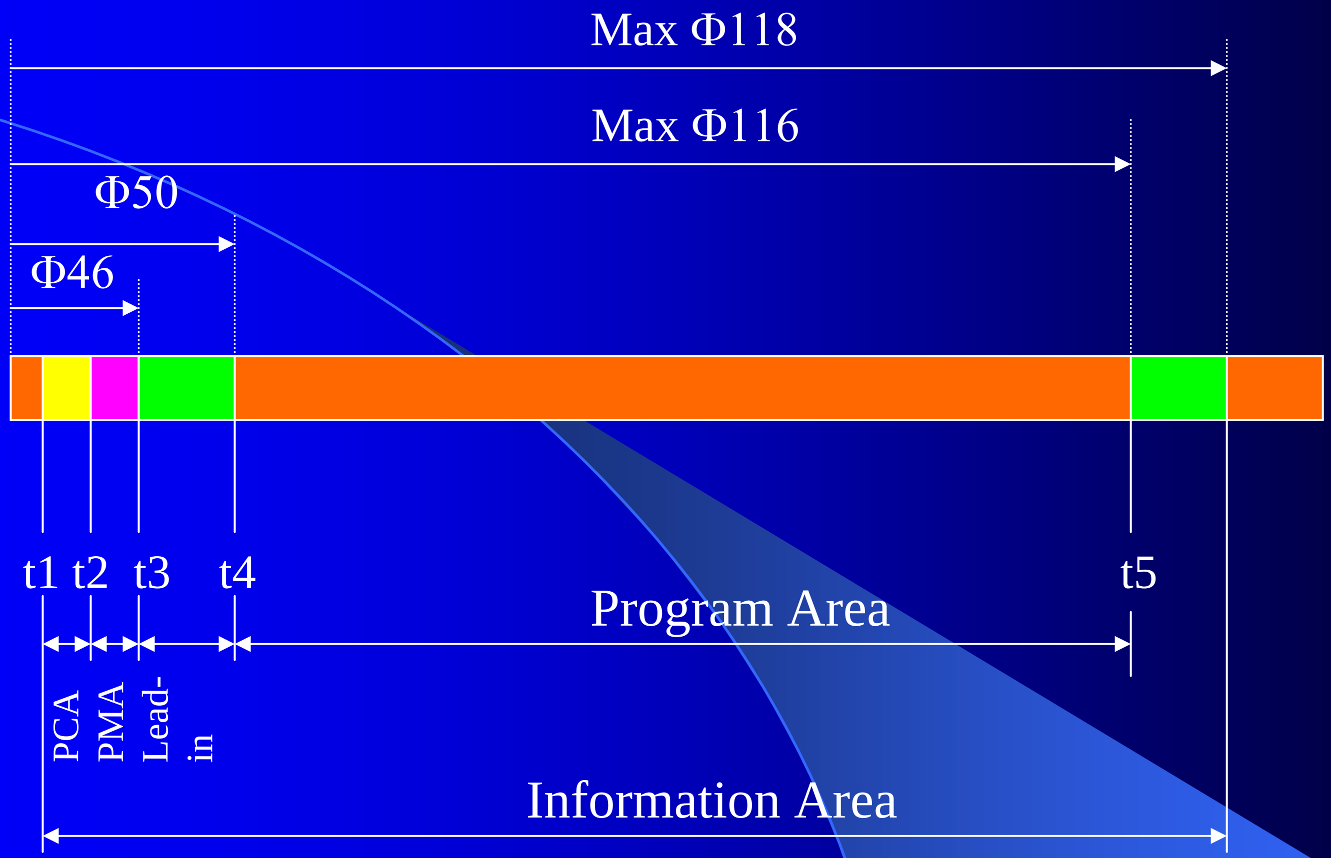
Recording process for CD-R



CD-R

- The Compact Disc Recordable (**CD-R**) format, officially named CD-WO (**Write Once**), is defined in the **Orange Book Part II**.
- Two areas are written to the inner portion (22.35 to 23 mm) before the lead-in radius → **PMA** & **PCA**.
- The **PMA (program memory area)** : -00:13:25 to 00:00:00 contains data describing the recorded tracks, **a temporary TOC**, as well as track skip information.
- The **PCA (power calibration area)** : - 00:35:65 to -00:13:25 allows the laser to automatically make an **Optimal Power Calibration (OPC)** test recording to determine proper laser power for data recording.
- The PCA contains a **test area** and a **count area**.

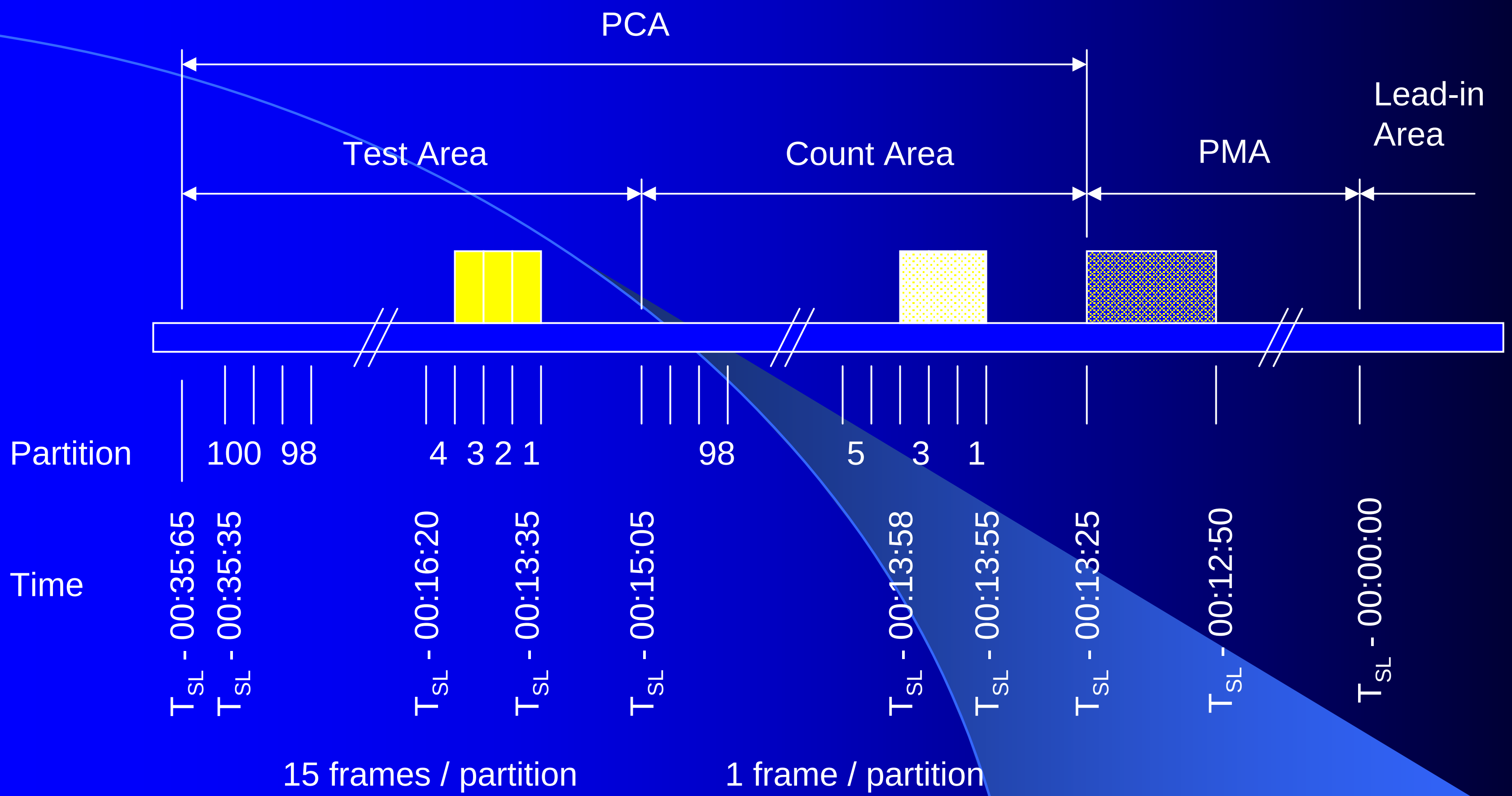
CD-R



t1 = Start time PCA = t3-00:35:65
t2 = Start time PMA = t3-00:13:25
t3 = Start time Lead-in = encoded in ATIP

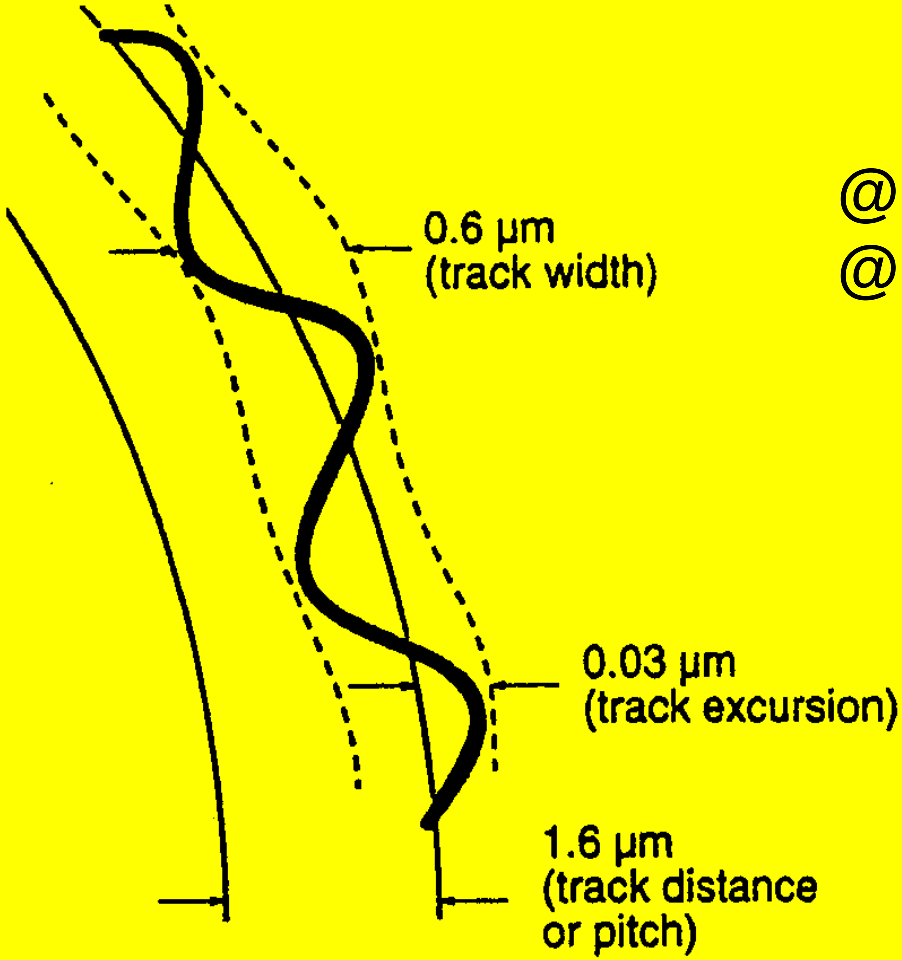
t4 = Start time program area = 00:00:00
t5 = last possible start time Lead-out encoded in ATIP

PCA & PMA



PMA : 50 Frames (first 10 frames for Disc Identification & last 40 frames for track dat

CD-R pregroove track



- @ 22.05 KHz
- @ used to guide the recording laser

Figure 9.25 The CD-R pregroove track is modulated with a ± 0.03-μm sinusoidal wobble with a frequency of 22.05 kHz.

Pre-groove modulation , ATIP

- By means of the **groove wobble frequency** (the carrier frequency) , the CD-R disc contains **motor control information**.
- By means of **ATIP** (**Absolute Time in Pre-groove** , modulation the carrier frequency) , the CD-R disc contains **time code information.**
- The ATIP time-code increases **monotonically** throughout the disc.

ATIP Data - CD-R

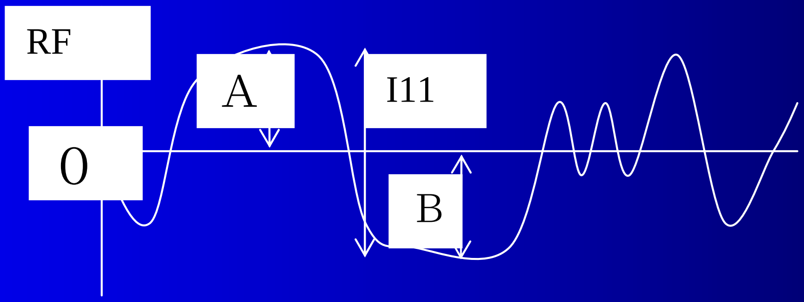
Target Writing Power (P ind)	: 5.9 mW
Reference Speed of P ind	: 1X
Disc Application Code	: General Purpose Disc
Disc Type	: Recordable
Disc Sub-type	: 0
Additional Info1	: Not Present
Additional Info2	: Not Present
Additional Info3	: Not Present
Start Time of Lead-in	: 97m28s00f
Start Time of Lead-out	: 74m52s31f

OPC Procedures

- Go the start of position of the test area of the PCA
- Start recording random EFM with different writing power
- $P_{ref.\ N} = P_{ind} * [1+0.4*(N-1)]$ N : the actual recording speed
- (Ex. P_{ind} = 5.9 mW for 1X ===> $P_{ref.\ N}$ = 5.9 mW)
- 15 test recordings DP = 0.043* P_{ref} = 0.254 mW
- (4.1,4.4,4.6,4.9,5.1,5.4,5.6,**5.9**,6.2,6.4,6.7,6.9,7.2,7.4,7.7 mW)
- Read out the recorded EFM data, and calculate b
- Target β = 4%
- The optimum writing power P_{w0} (β = 4%)
- Go the start of partition of the count area of the PCA
- End of OPC procedure

Beta (β)

Measures the shift from 0V of the central voltage of the 11T amplitude of RF signal after AC coupling.



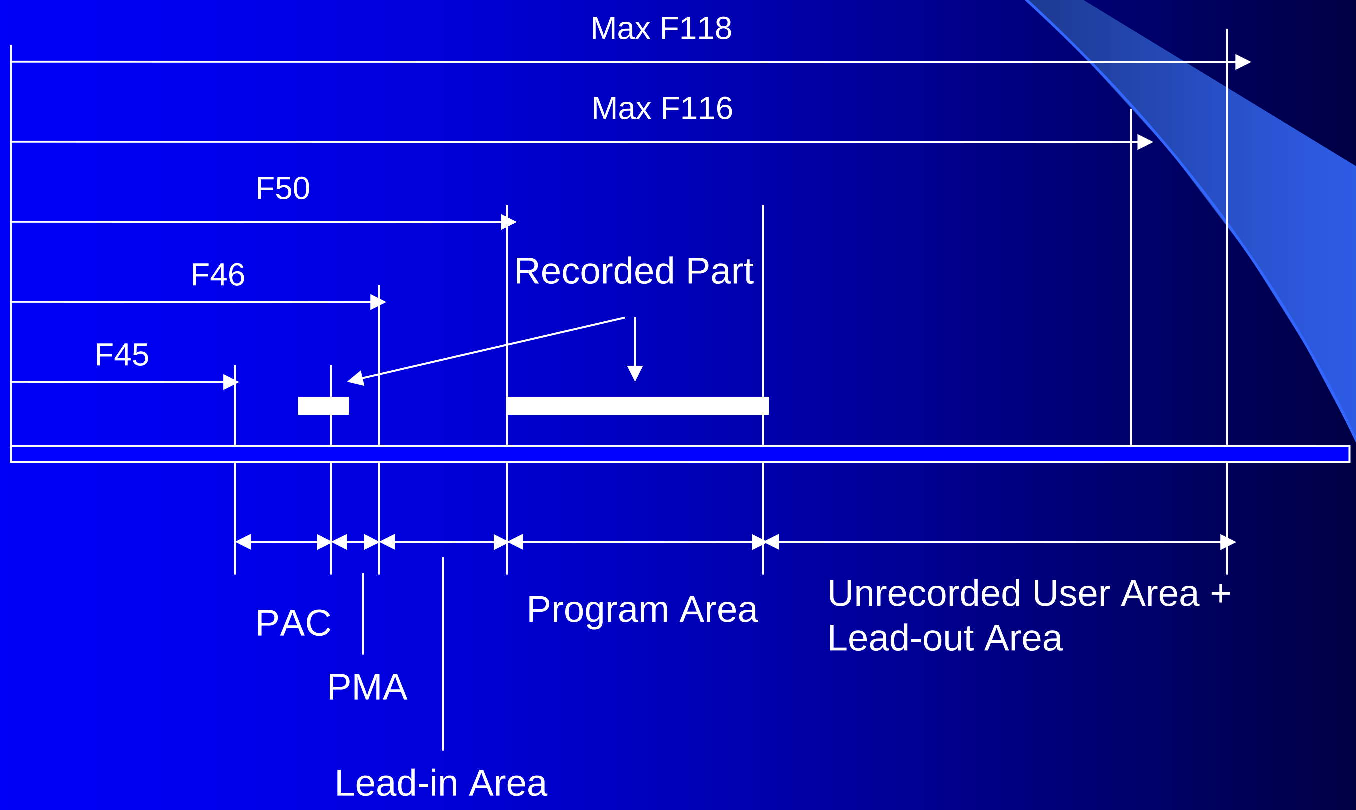
Beta = (A-B)/I11

CD-R染料種類簡介

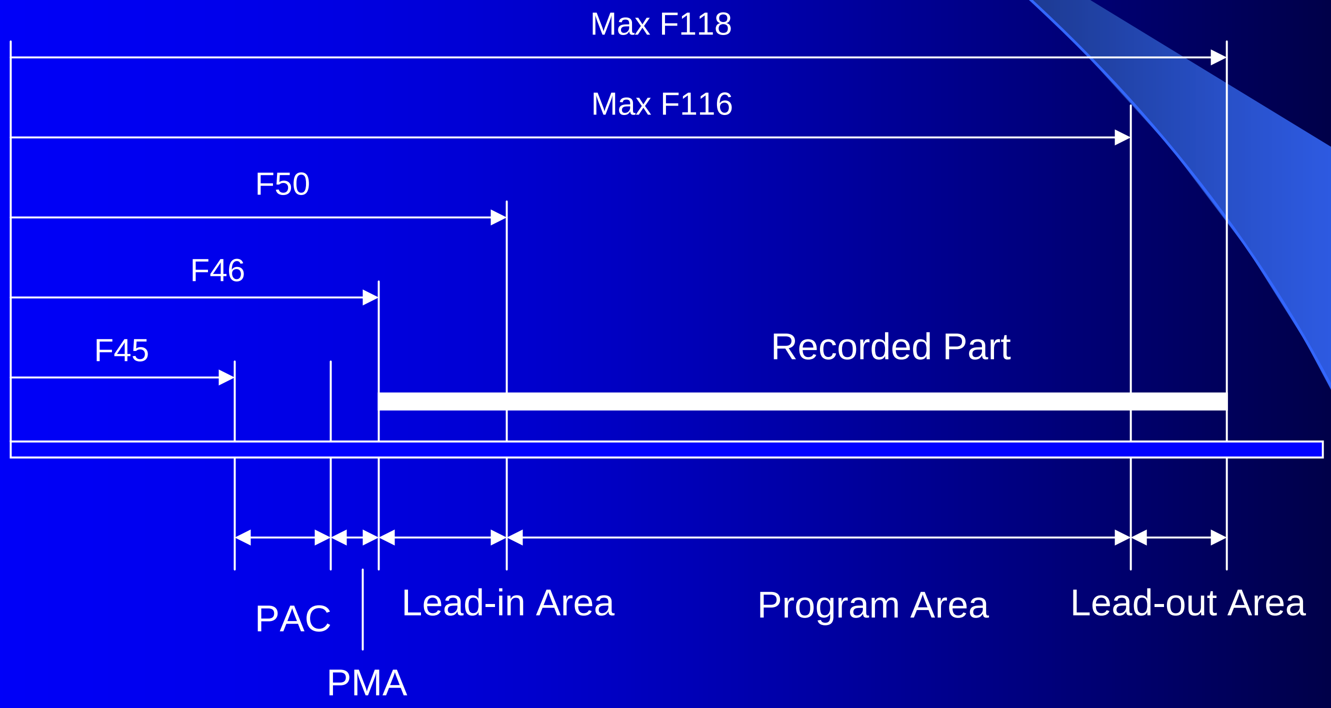
CD-R Dye

Cyanine	Phthalocyanine	Azo
太陽誘電	三井、柯達	三菱化學
藍綠色	淡黃色	深藍色
30~40年	>100年	永久保證
相容性佳	相容性可	相容性可
高速佳	高速可	高速差
<$3/g，不回收	<$25/g，可回收	

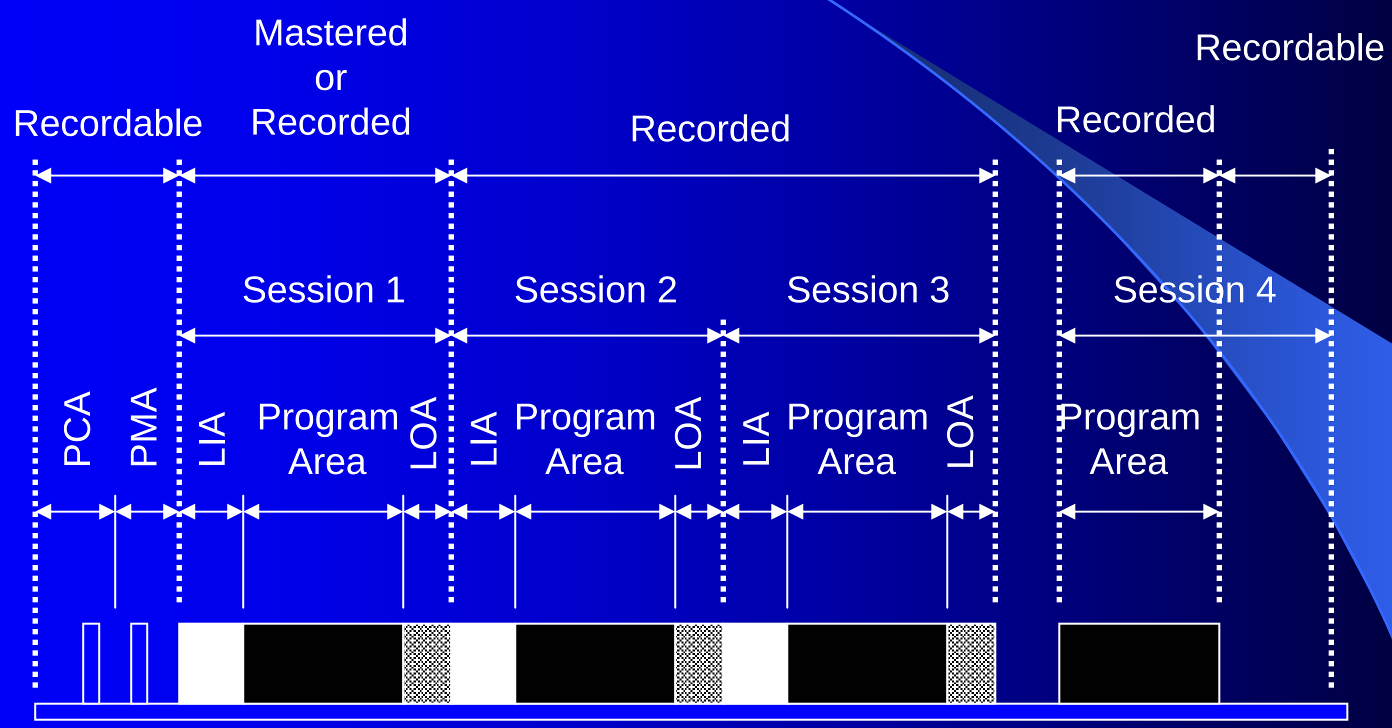
Partially Recorded Disc with One Session



Finalized Disc with One Session



Layout of a Multi-session Disc

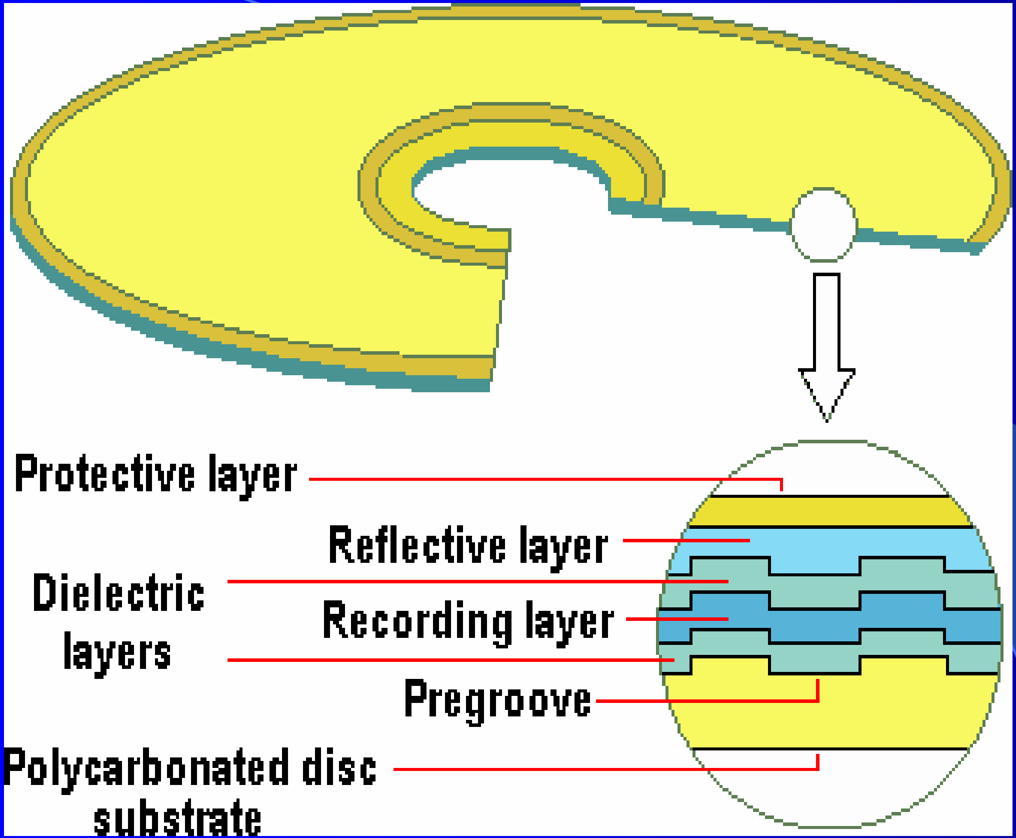


- Each time a session is created, about **13.5MB** of capacity is lost to lead-in (**8.8 MB**) and lead-out (**4.4 MB**) areas.
- The lead-out for the first session occupies about 13.2 MB.

CD-R

- By using the CD portion of the **Universal Disk Format (CD-UDF)**, CD-R discs can perform **packet writing** so that small amounts of data can be efficiently written.
- A packet contains **user data** along with associated **link blocks**. Special block called **run-in** and **run-out** allow a recorder to **synchronize data**, and they also contain **interleaved data** from other blocks.
- Written data comprises **a link block**, **four run-in blocks**, **user data**, and **two run-out blocks**.
- Two types of CD-R discs are sold : for **computer-use**, or for **music-use**.
- During recording, any interruption in the data stream at the recording laser will render a disc unusable.

Process for CD-RW



Mastering

Injection Molding

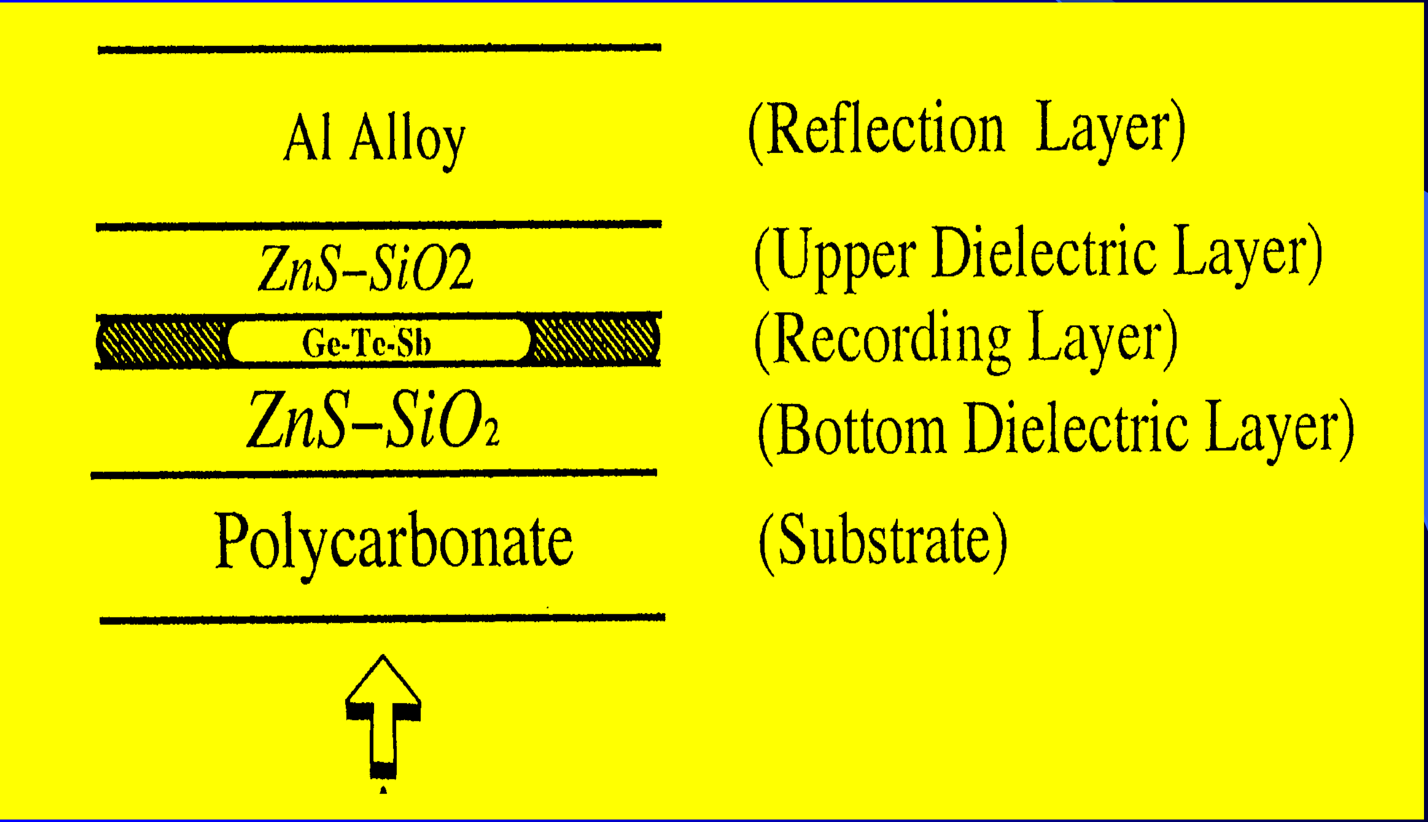
ZnS-SiO2/AgInTeSb /ZnS-SiO2/Al-Ti Sputtering

Lacquering

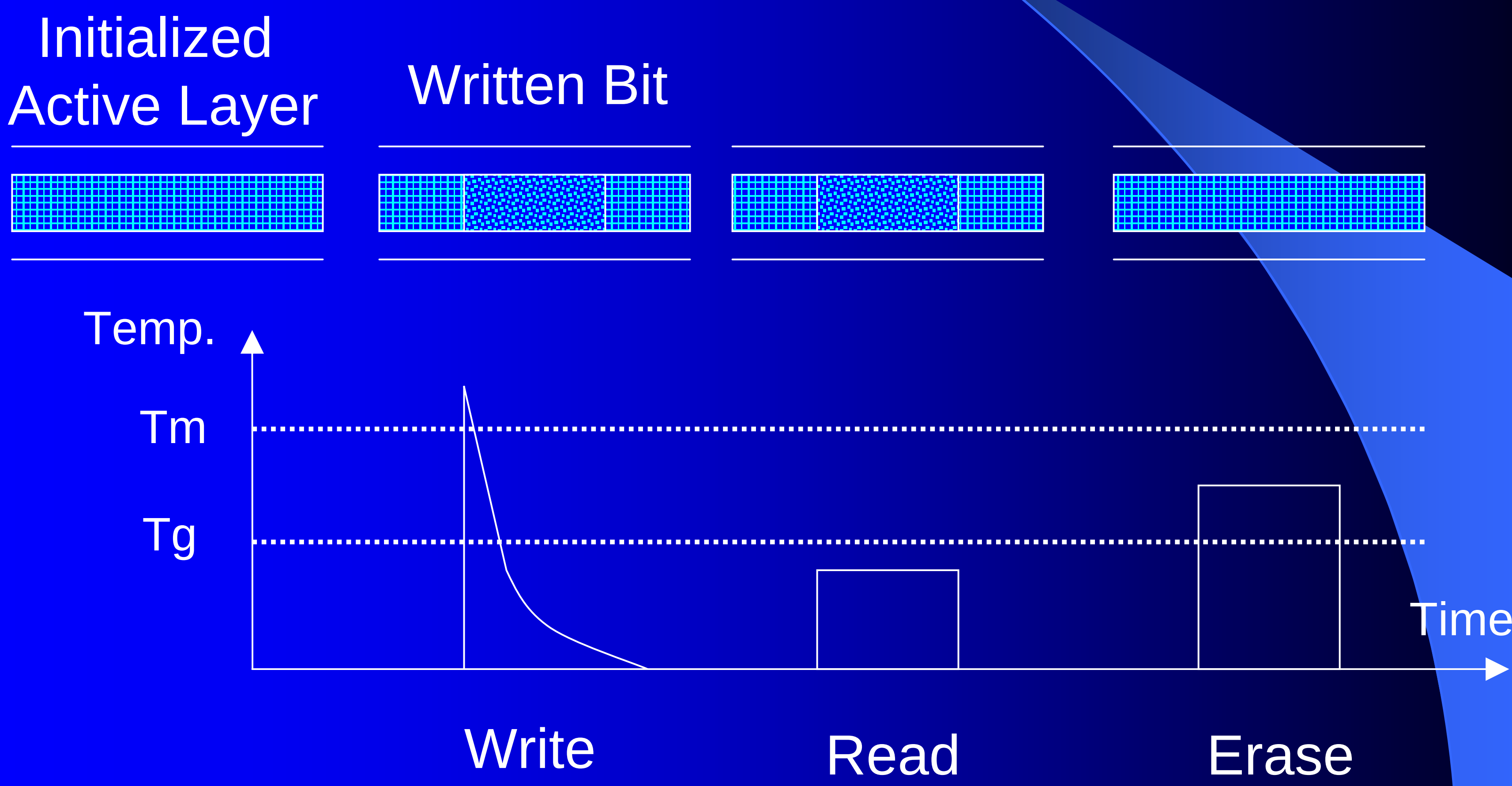
Initialization

Printing

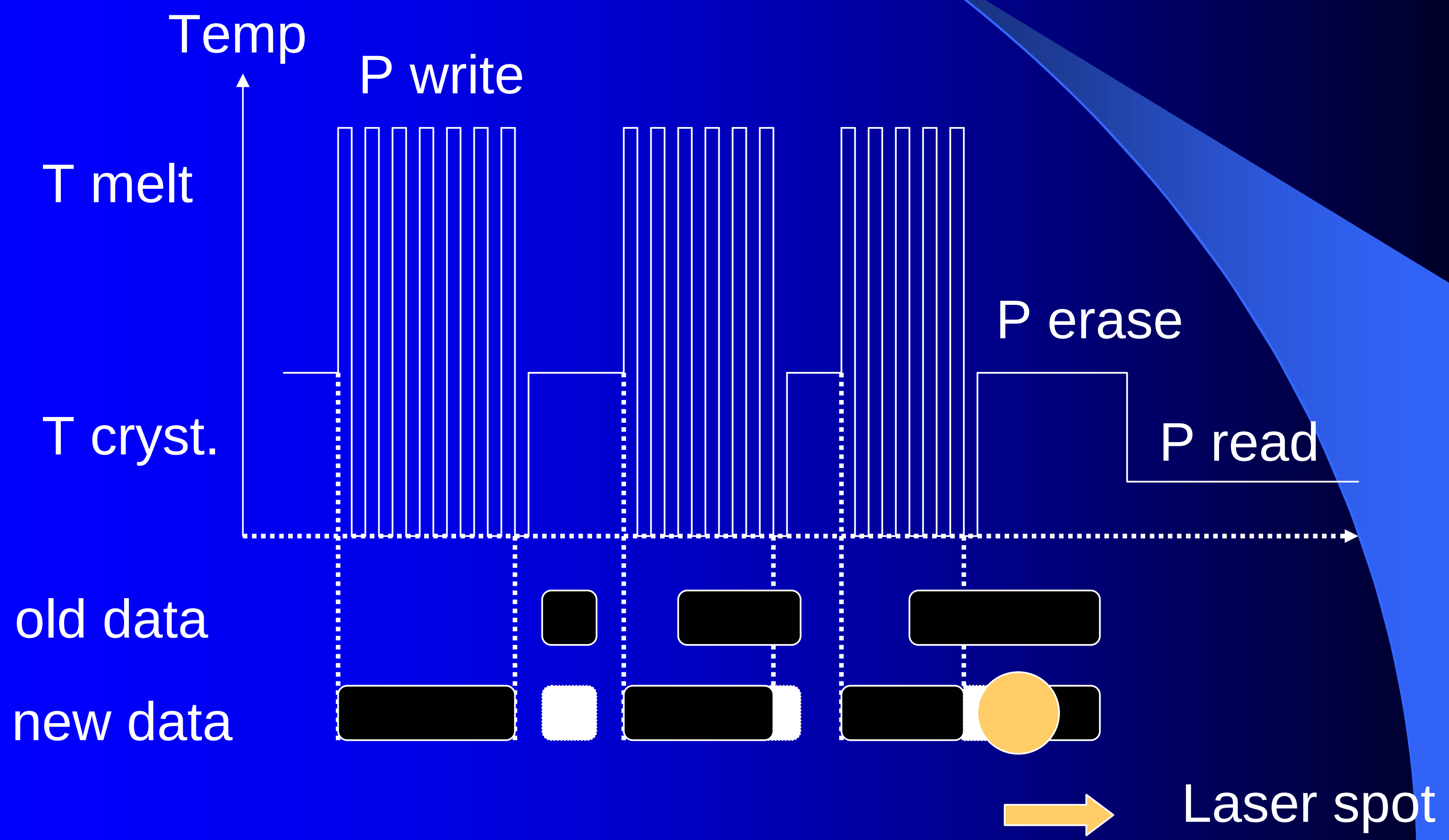
CD-RW Disc structure



Principle of phase change recording



Write Strategy for Phase-Change Recording Media



ATIP Data - CD-RW (1)

Target Writing Power (P ind)	: 11 mW
Reference Speed of P ind	: 2X
Disc Application Code	: General Purpose Disc
Disc Type	: ReWritable
Disc Sub-type	: 0
Additional Info1	: Present
Additional Info2	: Present
Additional Info3	: Not Present
Start Time of Lead-in	: 97m28s00f
Start Time of Lead-out	: 74m52s31f

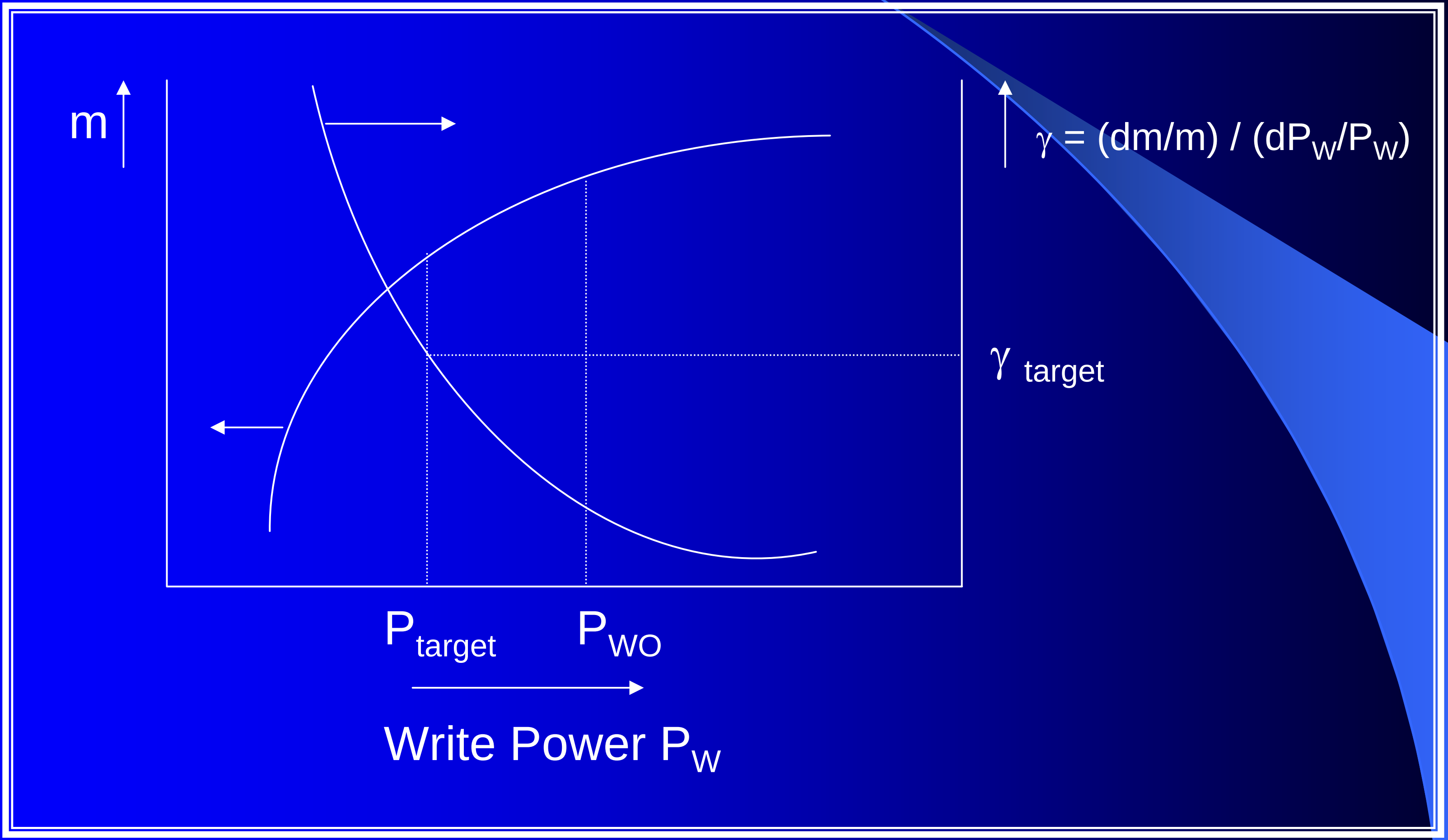
ATIP Data - CD-RW (2)

- Lowest Usable Recording Speed : 1X
- Highest Usable Recording Speed : 4X
- Power Multiplication Factor ρ : 1.15
- Target Gamma Value γ : 1.35
- Erase/Write Power Ratio ε : 0.50
- Erase/Write Power Ratio Compensation : 1.00

OPC Procedures - CD-RW

- Go the start of position of the test area of the PCA
- Start recording random EFM with different writing power
- Construct the modulation versus power curve m (P_W)
- Derive the normalized parameter γ
- (γ = slope = (dm/m) / (dP/dP_W))
- Construct the γ versus power curve γ (P_W)
- Determine P_{target} (= P_W at γ_{target})
- $P_{WO} = \rho * P_{target}$
- $P_{EO} = \varepsilon * P_{WO}$
- End of OPC procedure

OPC Procedures - CD-RW



Mechanical & Optical Properties

- **Retardation** (Birefringence) : **+/- 100 nm**

→ High BLER, Low Carrier / Noise Ratio & Optical readout

- **Radial deviation** : **+/- 1.6**

→ Loss of the HF signal & High Jitter Value

- **Tangential Deviation** : **+/- 0.6**

→ Loss of the HF signal & High Jitter Value

- **Axial Deflection** : **+/- 500 mm**

→ Focusing problem, Loss of the HF signal, High BLER & E32

- **Axial acceleration** : **+/- 10 m/s^2**

→ Affect **tracking performance** & **stability of focus servo system**.

CD electrical properties – CD-CATs

	specification		specification
SLD (mm)	< 46	BLER	< 220
SPD (mm)	49.6 ~ 50.0	E32	0
MID (mm)	< 116	I3	0.3 ~ 0.7
SVY (m/s)	1.2 ~ 1.4	I11	> 0.6
TRP (mm)	1.5 ~ 1.7	REF (%)	> 70
ECC (mm)	< 70	SYM (%)	+/- 20
PP	0.04 ~ 0.07	RN (nm)	< 30
XT (%)	< 50		
DEV	+/- 1.6	Jitter (ns)	< 35
DEFL (mm)	+/- 0.5		

The unrecorded disc

- **Radial tracking signal**

1. Normalized Push Pull Ratio : **0.5 ~ 1.0**
2. **Radial noise** : **< 30** ==> High RN causes the servo to skip track.
3. **Radial contrast** : **> +0.05**

- **Tangential tracking signal**

1. Locking frequency for the groove **wobble** : 22.05 kHz
2. **Normalized wobble signal** : **0.035 ~ 0.050**
3. **CNR of wobble** : **> 35dB**

- **Time encoding**

1. ATER : **< 10%**
2. Max. number of successive erroneous ATIP frames : **3 frames**

The recorded disc CD-R (RW)

- Reflection R_{top} > 0.65 (0.15 ~ 0.25)
- **Radial tracking signal**

1. Push Pull magnitude : 0.04 ~ 0.09 (0.04 ~ 0.11)
2. Radial contrast RCa : 0.3 ~ 0.6

- **Tangential tracking signal**

1. Locking frequency for the groove wobble : 22.05 kHz
2. CNR of wobble : > 26dB

- **HF signal**

1. I3R : 0.3 ~ 0.7 , I11R : > 0.6 (0.55 ~ 0.7), I3/I11 : (0.45 ~ 0.6)

==> Too low causes **decoding problem**.

2. Asymmetry : -15% < asym < +5% (-10% < b < +15%)

==> Too high causes **higher BLER**.

3. Jitter : < 35 ns

Relation between process parameter and signal

- Modulation : **Groove geometry**, **dye layer thickness**, **thickness of reflector**.
- Jitter : **dye layer thickness**.
- BLER : **thickness of dye solution**, **quality of dye solution.**
- Reflectivity : **groove geometry**.
- Requirements for Molding :

  1. Shot to shot < 3%

  2. Replication > 90%

  3. Depth variation < 10%
- Requirements for Coating :

  1. OD uniformity < 5%

  2. Temp. < 0.5 ^{o}C from average temp.

  3. Humidity as low as possible

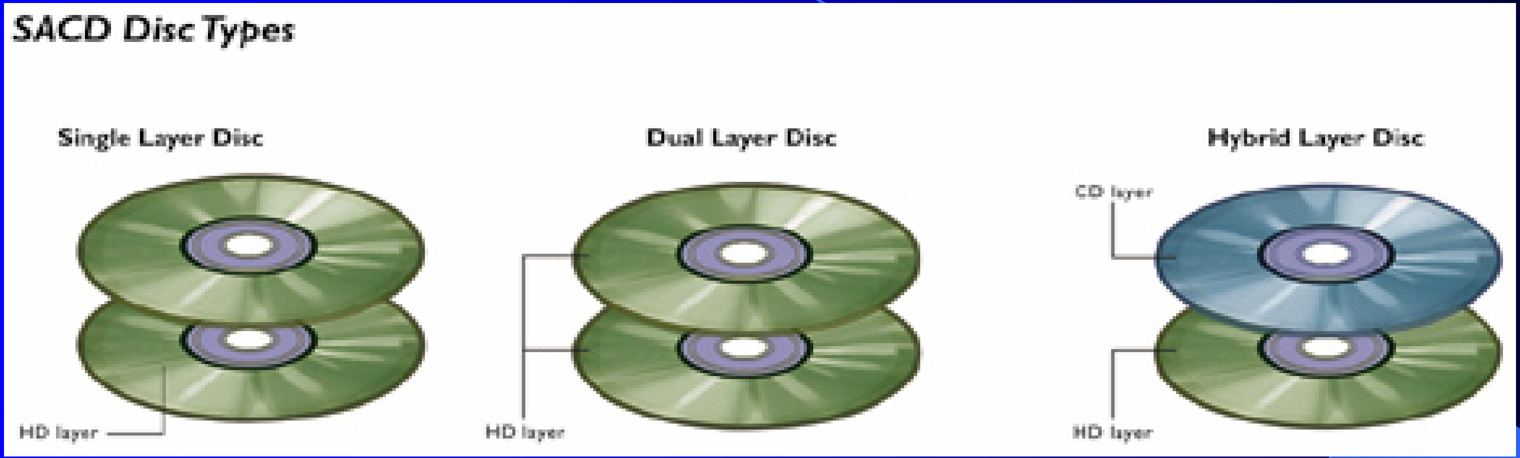
Compatibility - Written problem at high speed

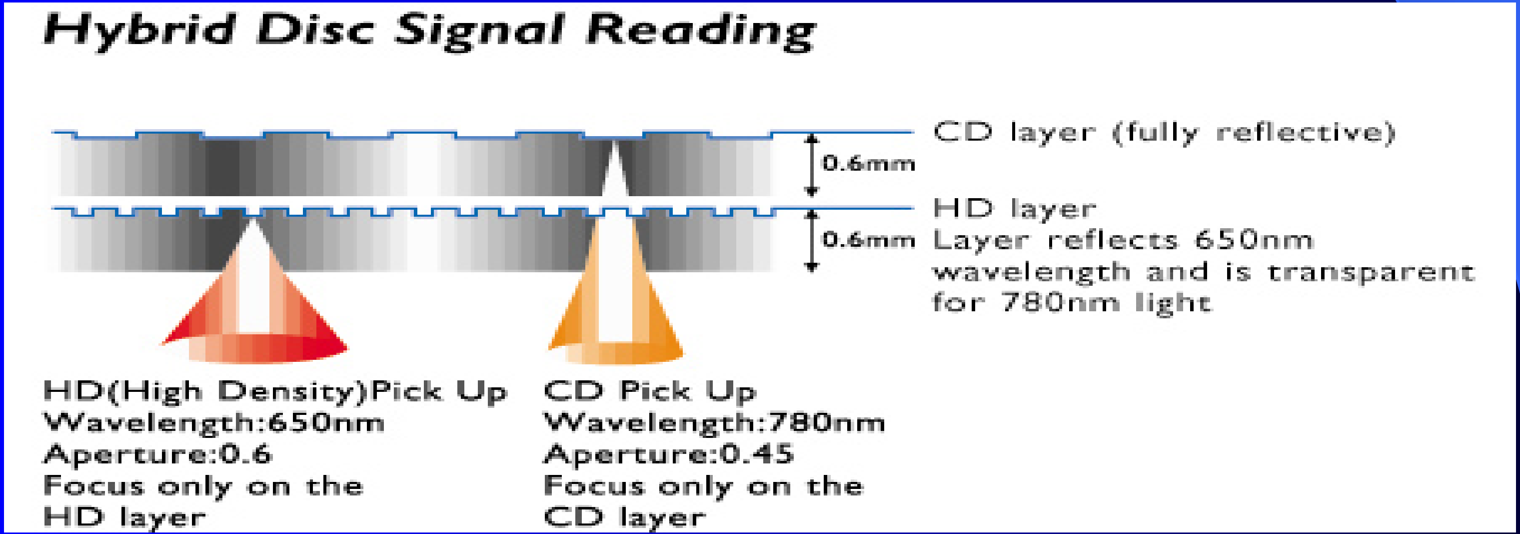
- Fail in PCA due to **poor disc sensitivity**.
- Fail in PCA due to **poor disc mechanical characteristics** (**Dishing** is more important than birefringence and ECC in high speed recording).
- Wrong disc type code.
- Weak tracking signals, weak ATIP and other signal error due to **poor groove geometry**.

Super Audio CD - SACD

- In 1999, Philips and Sony introduced the **high density Super Audio CD** standard, known as **SACD**.
- The SACD format also optionally allows for discs that hold both a high density **Direct Stream Digital (DSD)** data layer (containing both a 5.1-channel mix and a stereo mix), as well as a **Red Book** compatible (44.1-kHz/16-bit) data layer
- SACD discs use the same dimension as a CD. The laser wavelength is **650 nm**, the lens NA is **0.6**, the minimum pit/land length is **0.4 μm**, and the track pitch is **0.74 μm**.
- The SACD format includes single layer (4.7 GB), dual layer (8.5 GB) and hybrid disc (4.7 GB + 780 MB) construction.
- The **hybrid disc** is a dual layer disc that contains one layer of high density content and one layer of Red Book CD content.

Super Audio CD - SACD





Super Audio CD - SACD

- The innermost radius contains the disc **Master Table of Content (TOC)** containing information on tracks and timing as well as text data on the title and artist.
- The next radial area is given to **2-channel recording**.
- The next radial area is given to **multi-channel recordings**.
- The outermost radius is given to **extra data** such as text, graphics, and video.
- The SACD standard permits up to **255 tracks**.
- All SACD discs incorporate an **invisible watermark** that is **physically embedded** in the substrate of the disc.
- A process called **Pit Signal Processing (PSP)** uses a controlled array of pit widths to create both invisible and visible watermarks.

Super Audio CD - SACD

- Whereas all CD discs carry PCM data, all SACD discs carry **Direct Stream Digital (DSD)** data, in which audio signals are coded in **one-bit pulse density** form using **sigma-delta modulation**.
- The DSD modulation used on SACD uses a **sampling frequency** that is 64-times 44.1 kHz, or **2.8224 MHz**, and each sample is quantized as a **one-bit word**.
- Overall, the bit rate is **four times** higher than on a CD.
- The 2.8224 MHz sampling frequency of the one-bit DSD signal can be converted to variety of standard PCM sampling rate.

DSD coding

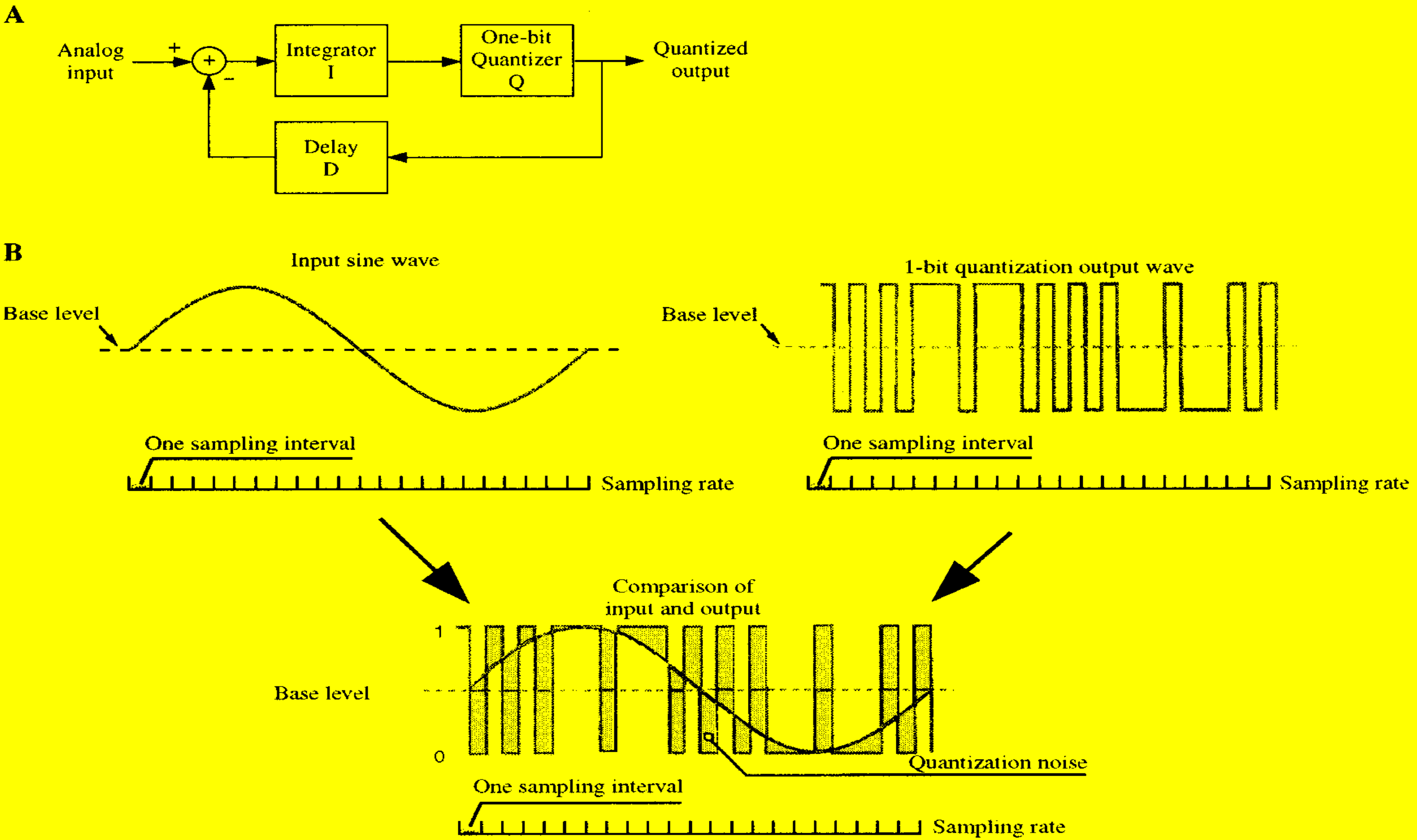


Figure 9.30 DSD coding is based on a sigma-delta coding technique. A. A sigma-delta modulator uses negative feedback to subtract a compensation signal from the input. B. The output signal from a sigma-delta modulator is a pulse-density waveform. (*Sony Corporation*)

Noise Shaping

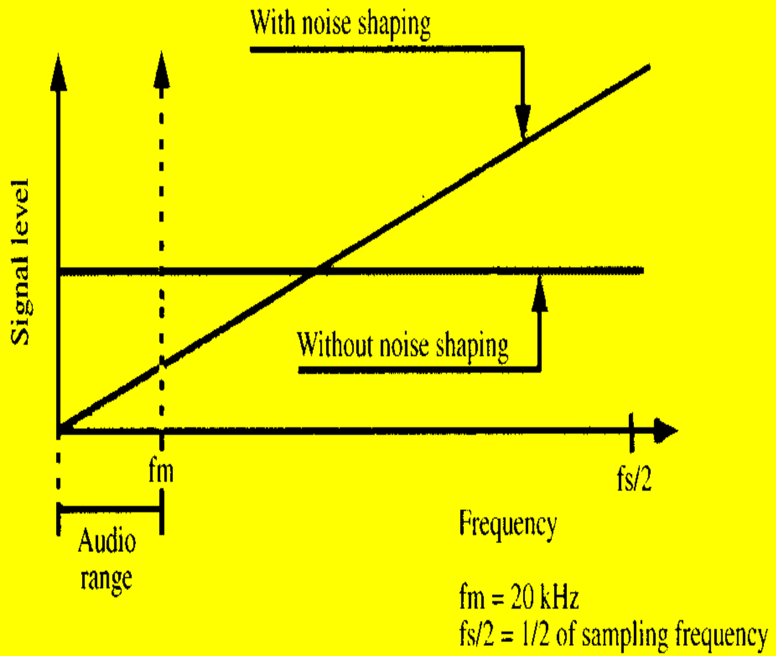


Figure 9.31 Noise shaping algorithms are designed to reduce the low-frequency (in-band) quantization error, but increase high-frequency (out-of-band) content.