Optical Storage Technology

The MiniDisc

System Overview

- The MD format was announced in **1991**. The MD was designed to be the **first recordable**, **erasable** optical-disc **audio format** for consumer applications.
- This disc format provides **random access** to data, its **small size** and **anti-shock** memory promote portability, and its data reduction system preserves high sound quality.
- The MiniDisc uses a **64-mm-diameter** optical disc permanently housed in a rigid **plastic cartridge** measuring **72 x 68 x 5 mm**.
- **Prerecorded** MD discs are quite similar to compact discs.
- **Recordable** discs use **magneto-optical technology**, and the cartridge has two shutters for the **optical pickup**, and the **magnetic head**.

System Overview

- The magnetic head **physically touches** the disc surface during recording, but head and disc wear are quite low.
- The **servo**, **control**, and **user interface systems** are similar to those found in CD players.
- When writing data, the laser's power is increased to heat the data surface, momentarily changing the magnetic properties of the data layer. The magnetic head is used to bathe the disc in a flux field, and in conjunction with the heating laser, writes data to the disc.
- AS in the CD, the MD uses **eight-to-fourteen modulation (EFM).** Also, a **Cross-Interleave Reed-Solomon code (CIRC)** is used during recording and decoding.

System Overview

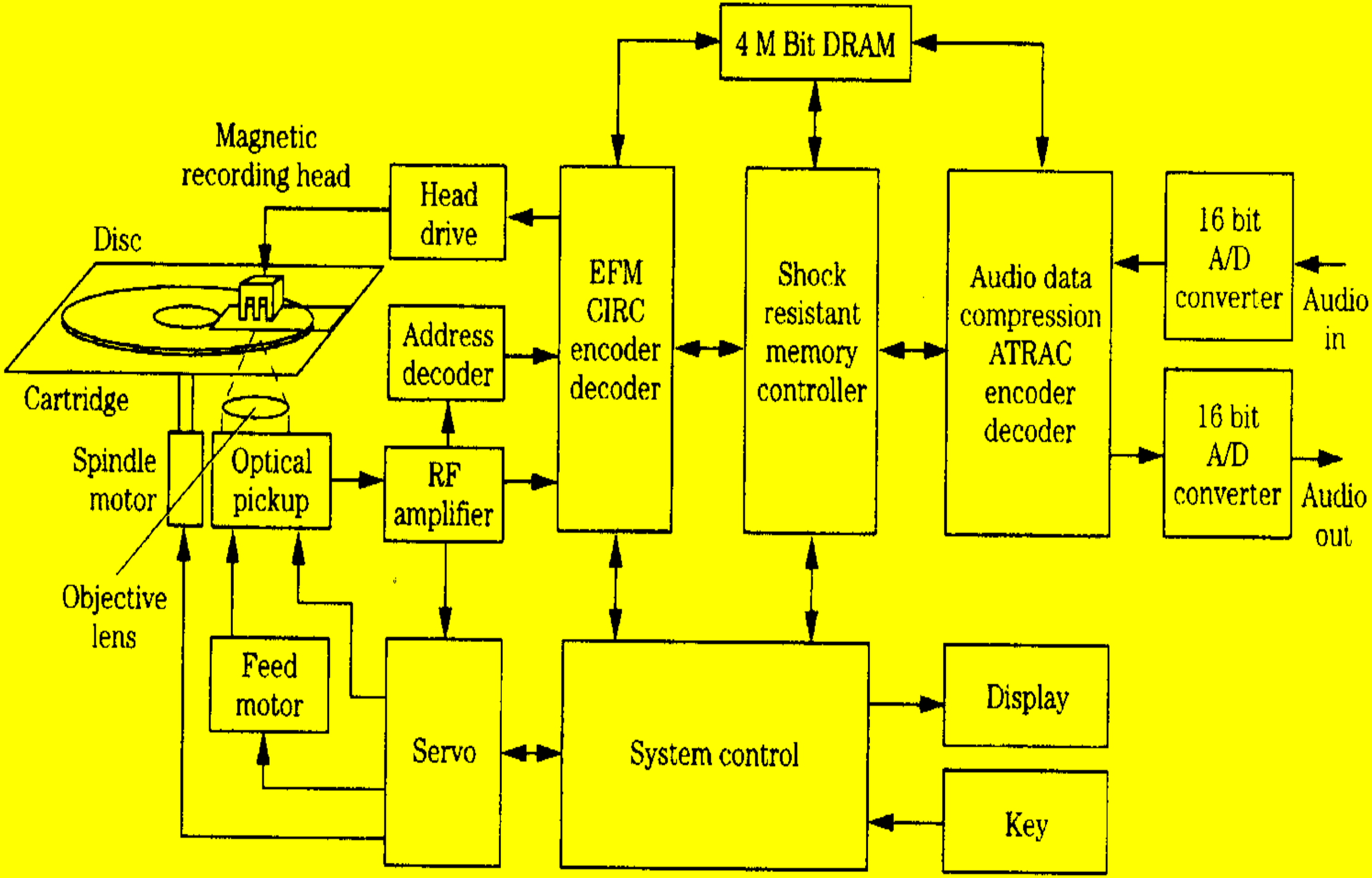


Figure 12.1 Block diagram of a MiniDisc recorder/player. Data reduction and magneto-optical recording differentiate it from the compact disc. (*Sony Corporation*)

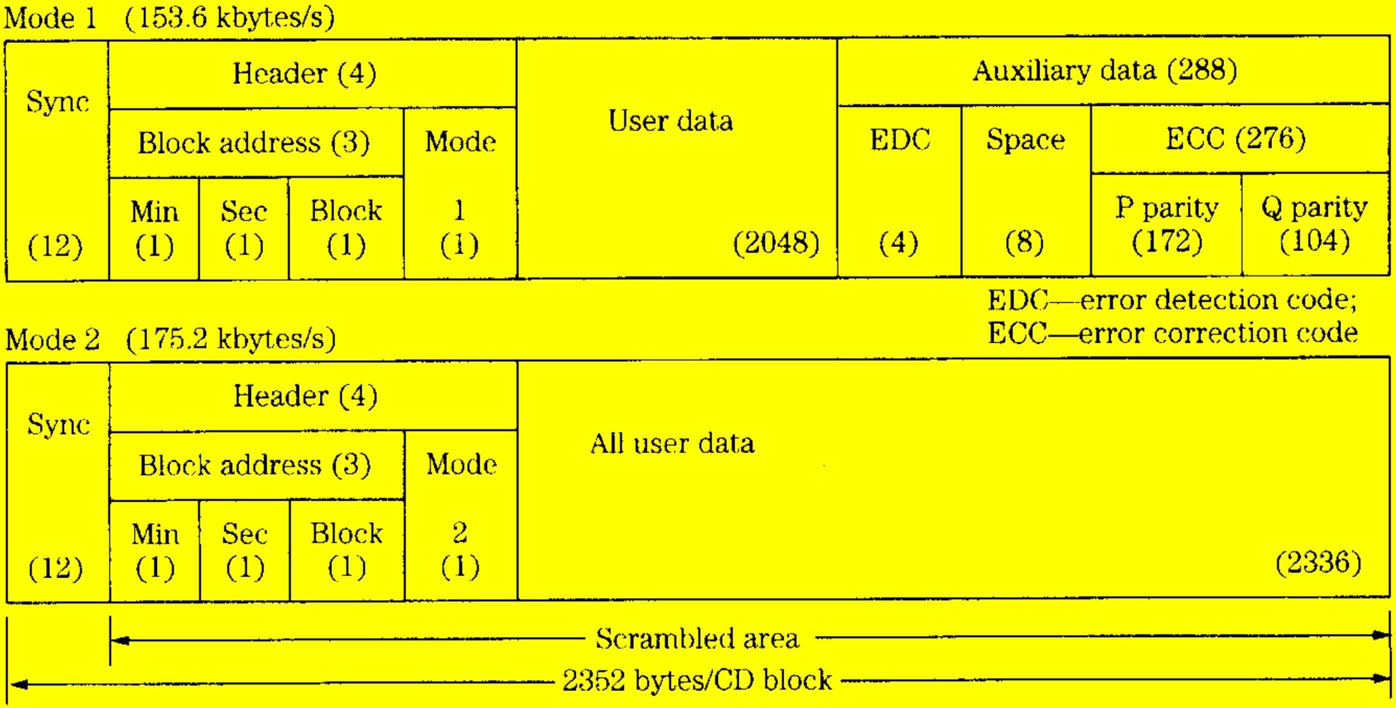
System Overview

- A **large memory buffer**, holding perhaps **4 Mbits** or more, gives the player great **immunity** from **physical shock**.
- The **ATRAC (Adaptive Transform Acoustic Coding) data reduction** algorithm uses a **MDST (modified discrete cosine transform** and **psychoacoustic) masking** principles to diminish data throughput to about **1/5** of its original volume, with minimal audio degradation.
- The MiniDisc specification is contained in the **Rainbow Book**.
- The MiniDisc was developed by **Sony Corporation**.

Signal Format

- The MiniDisc data format is very similar to that used in the **CD-ROM Mode 2** format. **98** CD **frames** comprise one **sector (2352 total bytes)**, which is equivalent to **13.3 ms** of playing time.
- CIRC interleave length is 108 frames, or 14.5 ms.
- Data is written only after being grouped into substantial **recording unit** called **clusters**, each contains **36 sectors**.
- The **first three** sectors of a 36-sector cluster serve as **link sectors** during recording; the **fourth** sector is reserved for **subcode data**. ATRAC-reduced **audio data** is stored in the remaining **32** sectors.
- After the last cluster sector is written, **error correction data** is written in the **first link sector** and **half of the second sector** in the following cluster.

CD-ROM



This area is equivalent to 1/75 s in CD audio, i.e., 16 bits × 2 channel × 44.1 kHz × 1/75 • 18,816 bits • 2352 bytes

1 mode per track
1—99 tracks per disc

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.

Signal Format

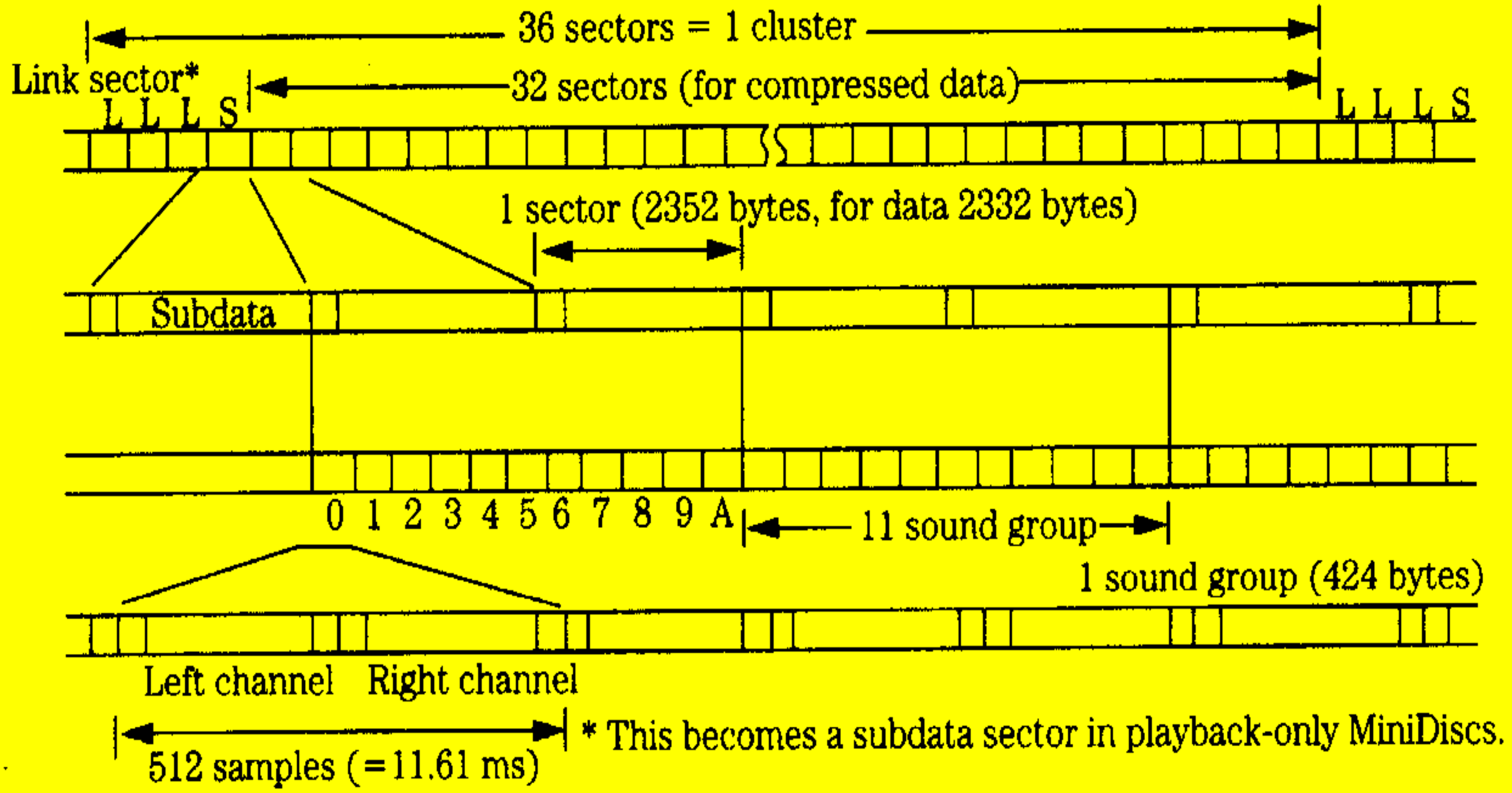


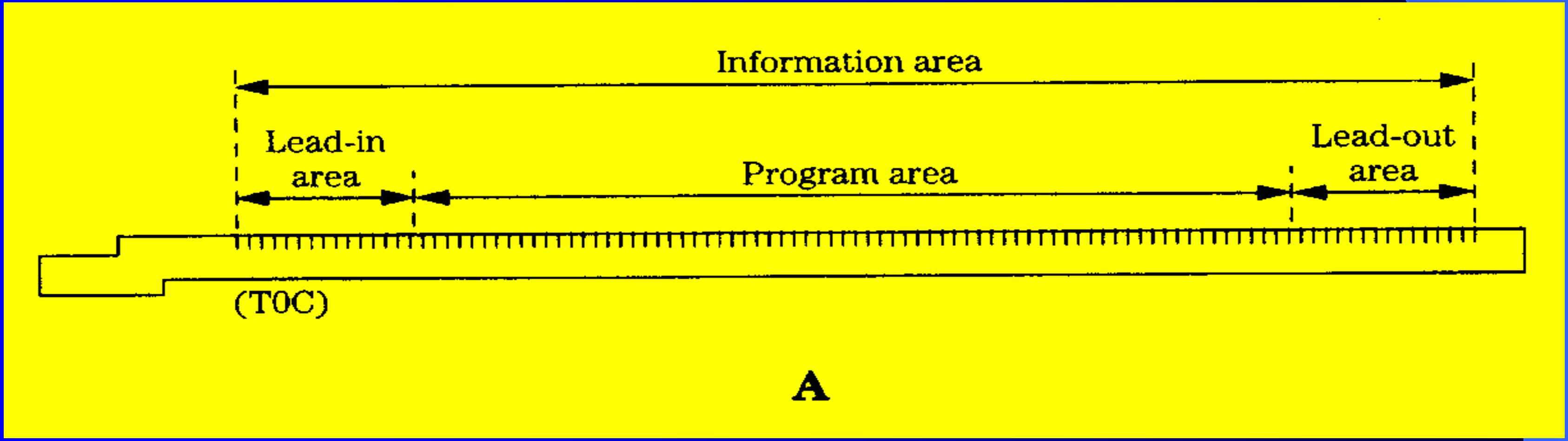
Figure 12.2 The MiniDisc data format is similar to that used in the CD-ROM Mode 2 format. However, sectors are grouped into clusters. (*Sony Corporation*)

Signal Format

- When MD is recorded **continuously**, the three sectors are not needed in a link area. All of the **first four sectors** can be used for **subcode data** holding text or other information.
- During ATRAC encoding, following data reduction, audio data is grouped into **424-byte units** called **sound groups**, with 212 bytes each for the left and right audio channels.
- **Eleven sound groups** are distributed into **two sectors**. In other words, each of the two sectors contain 11 x 212 = **2332 bytes** of **compressed audio data**.
- During playback, this data is decompressed with **one sound group** being equivalent to **512 samples (2048 bytes)** for both channels with a playing time of 11.6 ms.
- A variety of data type, with or without data reduction methods, can be placed on a MiniDisc.

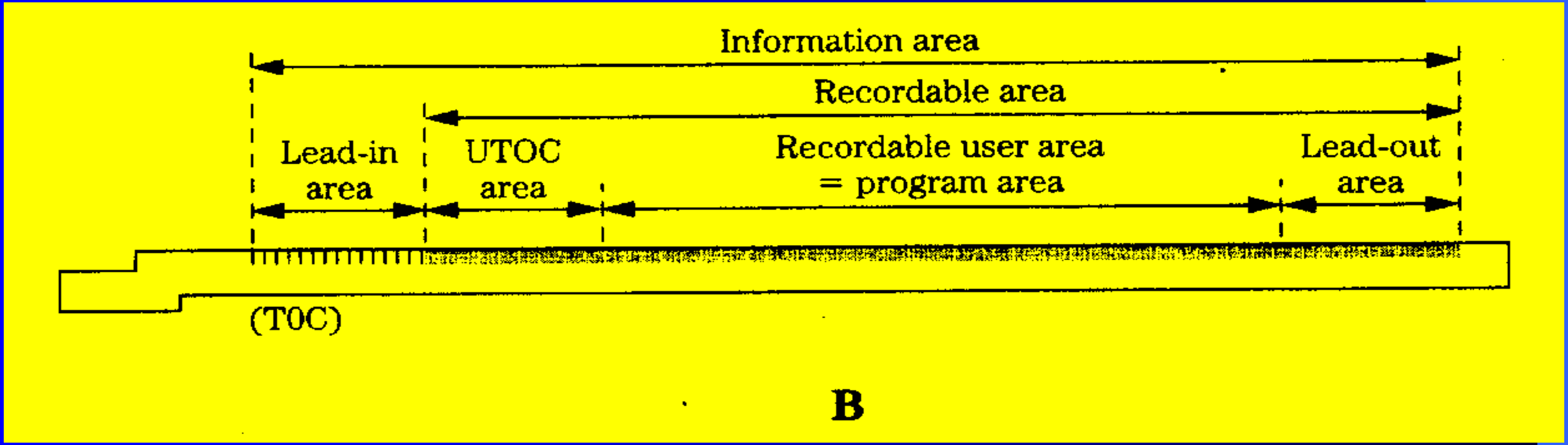
Disc Design

- A prerecorded MD disc is very similar to a CD. Data is recorded on a **spiral** from inner diameter to outer, with a **lead-in area** prefacing the **program area**, and a **lead-out area** following it.
- As in CD, prerecorded MD data is represented as **pits** impressed in a **polycarbonate** substrate, and the pit surface is covered by an **aluminum reflective layer**, as well as a **protective layer**.



Disc Design

- In the recordable disc format, a **user table of contents (UTOC) area** is inserted **between** the **lead-in** and **program areas**; it is used to **store information** on data that is **written** to a disc.
- The **table of content** in the lead-in area contains information on **recording power**, **disc recording time**, and **time of the UTOC**. The TOC in a recordable disc is stored as **pits** and **cannot be recorded**.



Disc Design

- **Recordable** discs are manufactured with a **pregroove configuration**. This pregroove guides the writing and reading laser within a spiral **track** that is **1.1 μm** in width, separated from adjacent track by **0.5 μm guard bands**.
- The groove is **70 nm depth**.
- Data is stored in a **terbium-ferrite cobalt (TeFeCo)** magnetic layer and sandwiched by two **silicon-nitride** dielectric layers, which are used to **concentrate laser heat** into the interior recording layer.
- An **aluminum** reflective layer placed over these layers is designed to reflect the reading and writing laser beams.
- The MD discs have an outer diameter of **64 mm**, inner diameter of **11 mm**, and substrate thickness of **1.2 mm**.

Disc Design

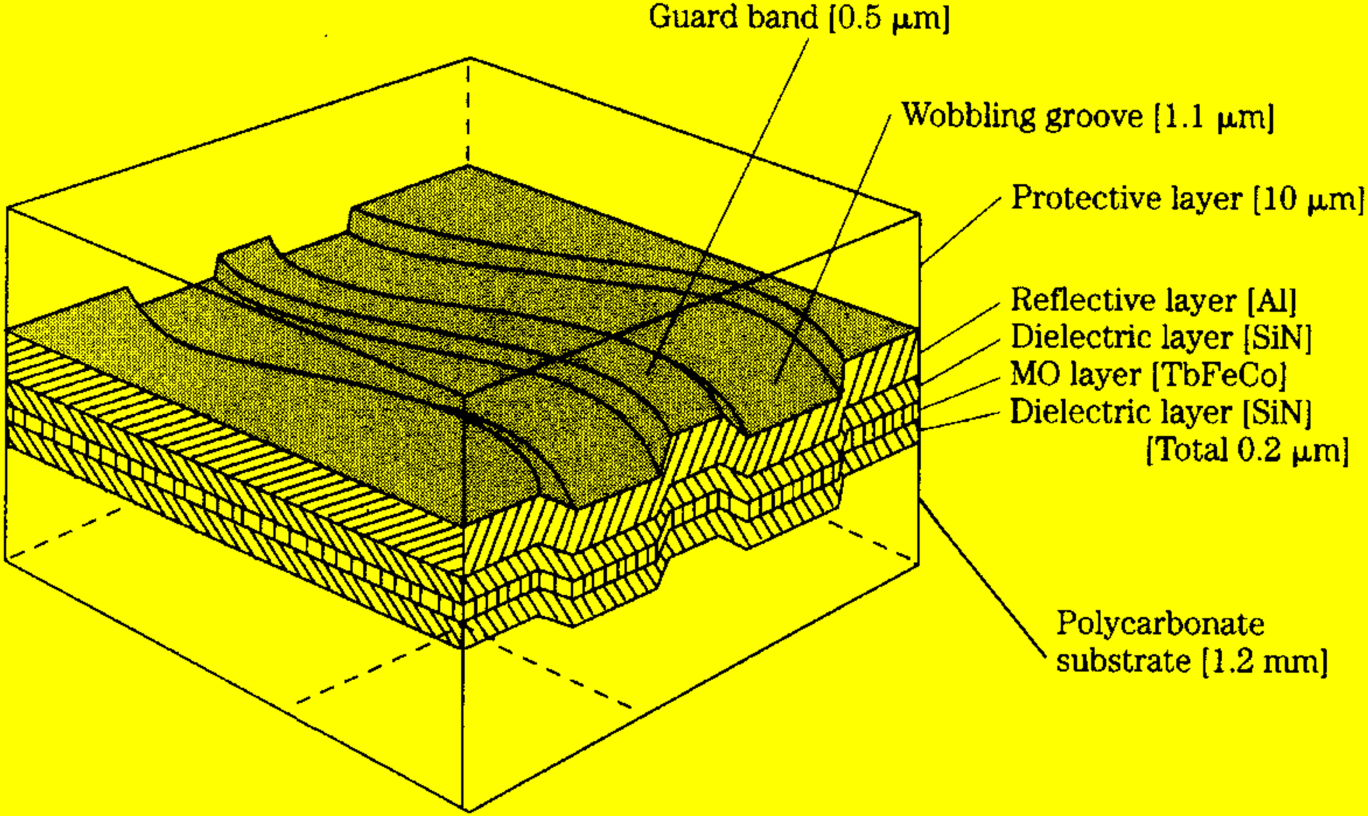


Figure 12.4 Recordable discs are manufactured with a pregroove configuration to guide the writing and reading laser within a spiral track. The MO recording layer is contained within dielectric layers. (*Sony Corporation*)

Disc Design

- **Random access** to stored data is an important feature of the MiniDisc system.
- The pregrooves are specially formed to create **addressing data**, promoting quick access. The grooves contain a **wobble** to create addresses in 13.3-ms intervals, effectively controlling both **absolute address time** and the **constant linear velocity speed**.
- The **user table of contents** contains **track number addresses**; track addresses **can be edited** to reflect changes in the recorded contents of a disc.
- A **hybrid** MD format combines **prerecorded** and **recordable areas** on one disc. A UTOC is necessary to log recorded tracks.

Disc Design

- All MD players are equipped with a **buffer memory (4-Mbit)** that provides **continuous data flow** even data reading from the disc is interrupted.
- In the MD, because of data reduction, the **required data rate** is about **1/5** that of CD, thus a corresponding smaller memory can be used.
- The pickup **reads** data from the disc at a rate of **1.4 Mbps**; however, through data reduction, the required **output rate** from the buffer is only **292 kbps**.
- The **ATRAC decoder** accepts the 292-kbps rate and output data at a 1.4 Mbps rate.
- The buffer permits **continuous data input** while discontinuously recording, and during playback provides continuous output.

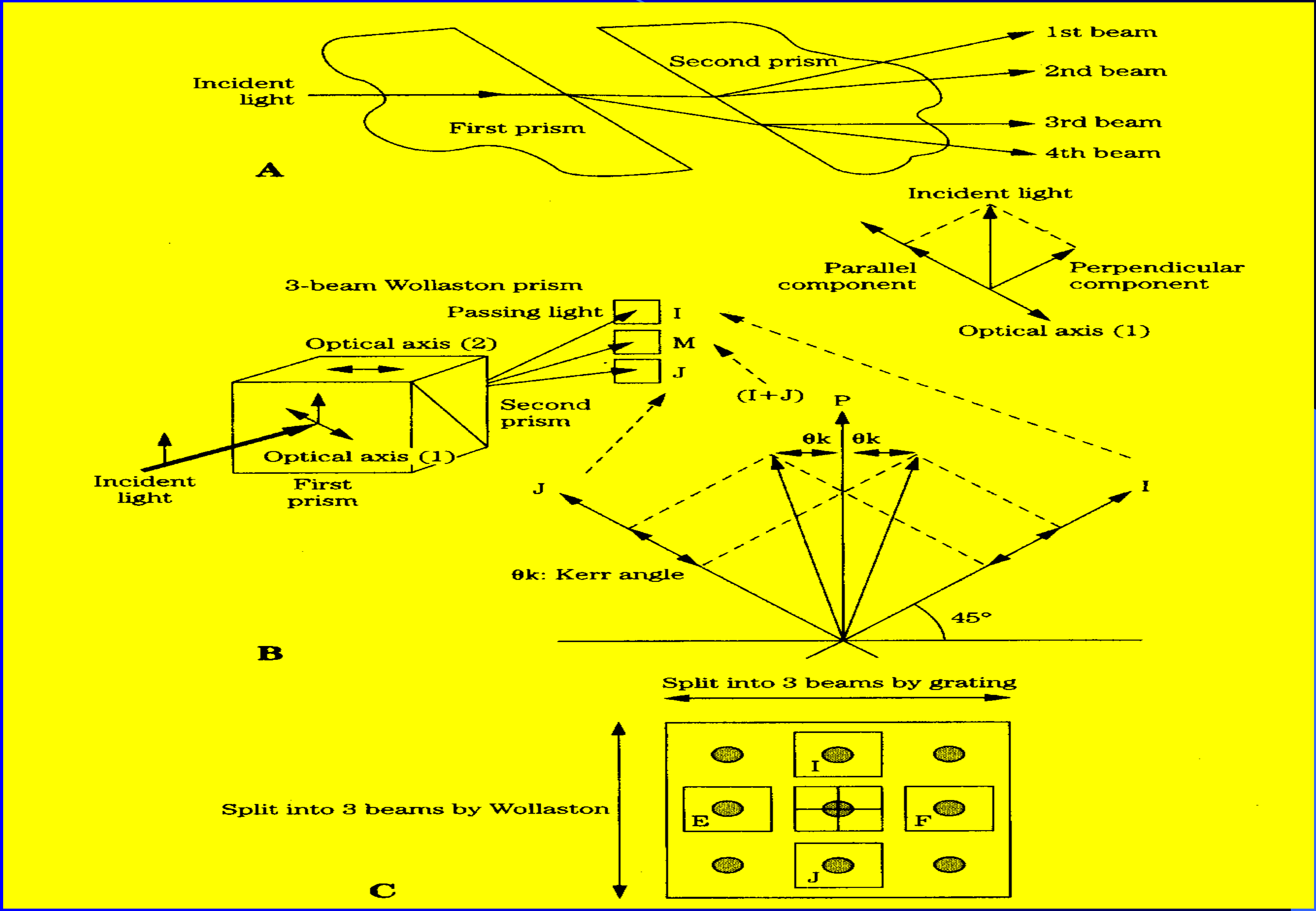
Optical Pickup

- The MD format is designed to play back two types of discs : **prerecorded** and **recordable discs**.
- Because these two disc types are quite different, they cannot be read using the same method.
- **Prerecorded** MD discs are read similarly to CD; **pits** are detected by monitoring varying light intensity. A laser beam (**780 nm**) of approximately **0.5 mW** of power is focused on the pit surface. The objective lens has a NA of **0.45**.
- **Recordable** MD discs can be read with the same pickup, but the **pickup** must be **modified** because the data encoded on the magneto-optical surface does **not** present variations in the intensity of reflective light.
- A polarized beam splitter **(PBS)** must be included to detect differences in the **plan of polarization** of reflected light.

Optical Pickup

- The light reflected from a MO disc is analyzed according to the **Kerr effect**; the **plane of polarization** of the reflected light **rotates** slightly differently, depending on the contents of the **perpendicularly magnetized data**.
- The **Kerr angle** can be used to read data. In the case of recordable discs, the Kerr angle is about **0.3º**; the analyzer detects this difference in the angle of rotation of polarization plane according to **direction of the magnetic domain** and redirects light to photodiodes.
- In a MD disc, a servo actuator system is used to provide **autofocusing** via an **astigmatic detection method**;, and **autotracking** via **three-spot detection method**.
- The autofocusing system : <= +/- 1 μm.
- The autotracking system : <= +/- 0.1 μm.

Optical Pickup



Magneto-optical reading

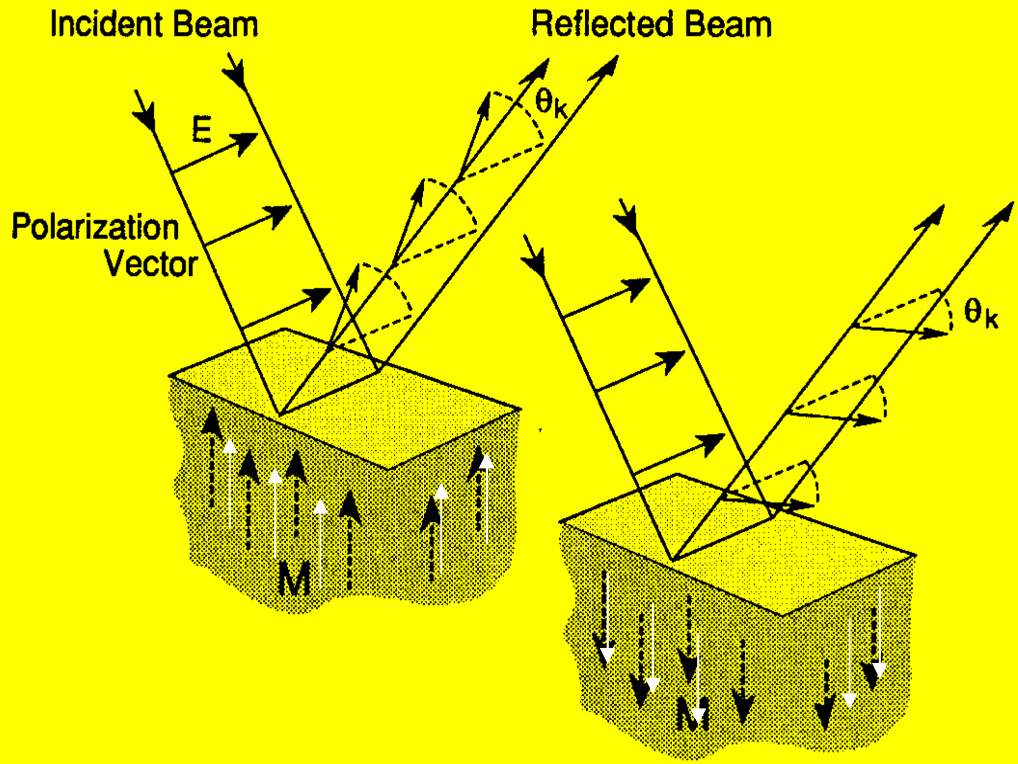


Figure 1.20. Schematic diagram describing the polar magneto-optical Kerr effect. Upon reflection from the surface of a perpendicularly magnetized medium, the polarization vector undergoes a rotation. The sense of rotation depends on the direction of the magnetization vector **M**, and switches sign when **M** is reversed.

Optical Pickup

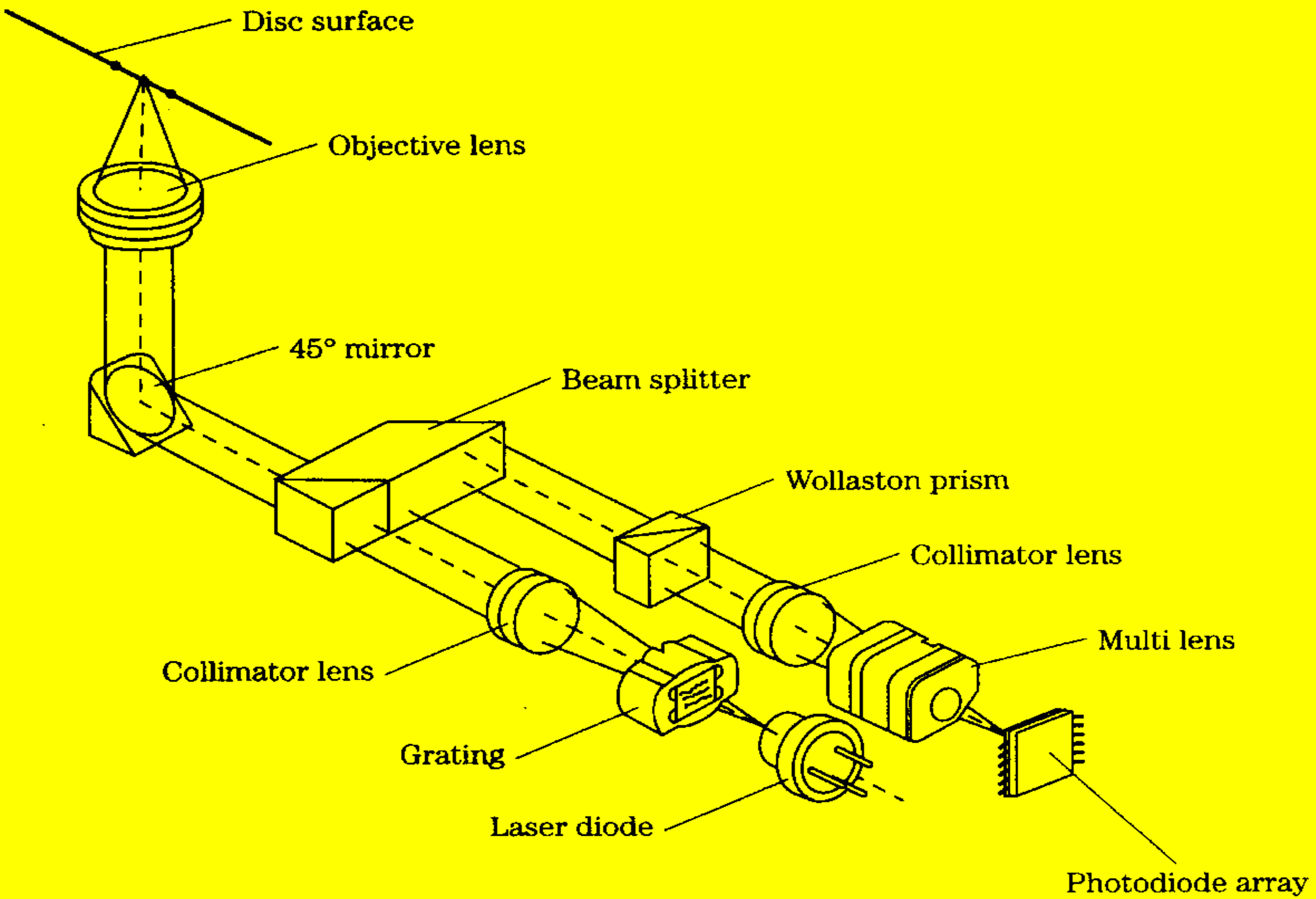


Figure 12.6 Complete MiniDisc laser-optic assembly. (*Sony Corporation*)

MO Recording and Field Modulation

- Recording is performed by bathing the data surface with the appropriately **oriented magnetic field** while heating the data surface. Laser power is about 4.5 mW.
- When the heating laser is withdrawn, the data is " **frozen** " in the magneto-optical layer.
- These requirements are achieved with components with **low power consumption**, **small size**, and **low cost**.
- A highly stable magnetic layer of terbium ferrite cobalt was developed; it allows flux reversals with a magnetic field as low as **80 oersteds** at the **Curie temperature.**
- At **room temperature**, the coercivity of the layer is more than **10000 oersteds**.
- A **magnetic head** was developed that allows fairly **rapid flux reversals** (within **100 ns**) at low power level.

MO Recording and Field Modulation

- Coercivity is inversely proportional to applied temperature. When the material's Curie temperature (~ 180 ℃) is reached, the coercivity is so diminished that only a very weak field is needed to magnetically orient the material.
- As the area moves away from the beam, the area cools below the Curie temperature, the applied magnetic field is withdrawn, and data is retained in **chevron-shaped** magnetized areas.
- The head **contacts** the disc surface to maintain a **close and unvarying distance** from the MO layer, about **10 μm** within the disc.
- In some MO systems, data must be erased prior to writing new data. In practice, we can use **two lasers**, one for **erasing**, and one for **writing**.

MO Recording and Field Modulation

- In the MiniDisc system, **magnetic-field modulation overwrite (MMO)** method is used to directly write new data over old, by modulating the magnetic field at high speed, creating specific orientations to represent the applied data signal.

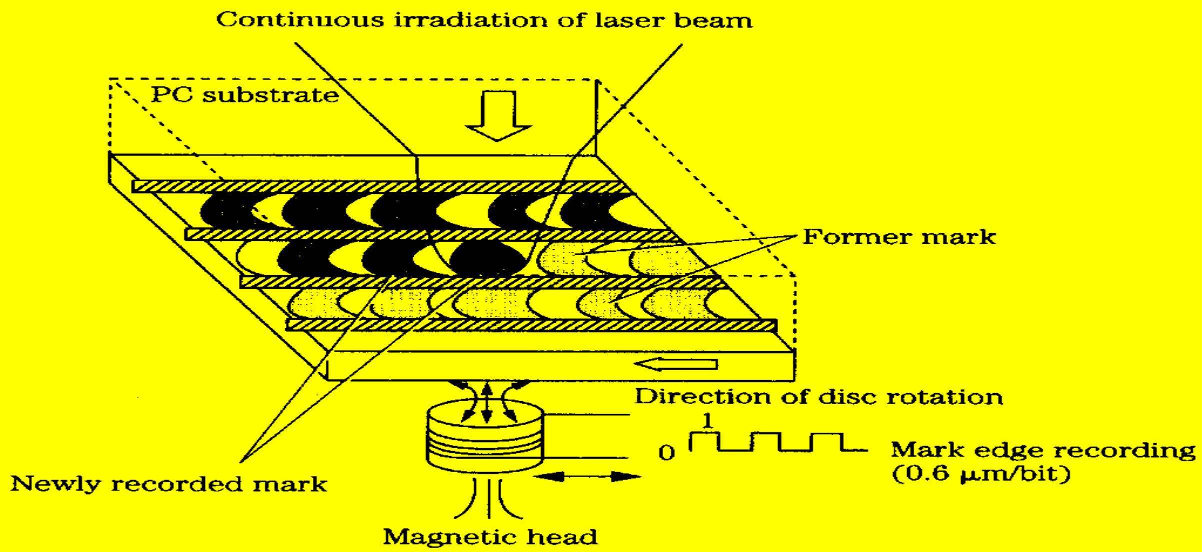


Figure 12.7 A magnetic-field modulation overwrite (MMO) method is used to directly write new data over old, by modulating the magnetic field at high speed; the laser is always on during recording.

MO Recording and Field Modulation

- The MMO method provides the **same linear velocity** as in the CD format (1.2 to 1.4 m/s), provides the **same density** as in CD discs (0.6 μm/bit), and is compatible with the 13.3-ms wobble addressing used in recordable MDs.
- With MMO experiments showed that **block-error rates** dropped below **20** per second at a linear velocity of 1.2 m/s.
- In **conventional laser modulation** :

✓ Laser power is varied.

✓ Pattern shapes are often irregular

✓ Pulsed laser methods are needed to overcome this, but increase cost and complexity.

✓ Can only tolerate a +/- 10% variation in recording power.

✓ Sensitive to disc tilt.

MO Recording and Field Modulation

- In **magnetic-field modulation overwrite** :
- ✓ Laser power is always on.
- ✓ The heating and cooling process above and below the Curie temperature isothermal line determines the shape and length of the recorded binary 1 or 0 patterns.
- ✓ The recorded pattern is highly symmetrical, jitter is reduced.
- ✓ a +/- 20% variation in recording power is permitted.
- ✓ Also demonstrated a resistance to the effect of disc tilt.
- Although the magnetic head touches the disc surface during recording, the MO record/erase cycle is long-lived.
- Writability is more than 1,000,000 cycles.
- Readability is more than 10,000,000 times.

ATRAC Data Reduction

- The MiniDisc system uses data reduction based on **psychoacoustic principles**.
- Prior to storage, the audio data rate of 1.41 Mbps is compressed using a **perceptual coder** to a rate of **292 kbps** approximately **1/5** that of the original.
- The **ATRAC (Adaptive Transform Acoustic Coding)** algorithm was developed to perform the encoding and decoding. Without ATRAC, an MD disc would hold only 15 minutes of audio program.
- ATRAC transform coding is based on **non-uniform frequency** and **time splitting concepts**, and assigns bits according to rules fixed by a **bit allocation algorithm**.
- ATRAC changes the recorded signal according to the **ear's dynamic sensitivity**.

ATRAC Data Reduction

- ATRAC analyzes the signal in each block to determine the content in **different frequency bands**.
- More specifically. ATRAC divides the audio signal into **three subbands**, which are then transformed into the **frequency domain** using a **variable block length**.
- Data in these bands is **quantized** according to **dynamic sensitivity** and **masking characteristics**, again based on a human auditory model.
- During **decoding**, the quantized spectra are reconstructed according to the bit allocation method, and synthesized into the output audio signal.
- The ATRAC encoding algorithm can be considered in three parts : **time-frequency analysis**, **bit allocation**, and **quantization of spectral components**.

ATRAC Data Reduction

- The time-frequency analysis uses **subband** and **transform coding techniques**.
- Two **quadrature mirror filters (QMF)** divide the input signal into **three subbands** : low (0 Hz to 5.5125 kHz), medium (5.5125 to 11.025 kHz), and high (11.025 to 22.05 kHz).
- Following splitting, contents are examined to determine **length of block durations**.
- Signals in each of these bands are them placed in the frequency domain with the **MDCT (modified discrete cosine transform) algorithm**.
- The coefficients are formed into **512** non-uniform frequency groups, with **128** spectra in the **low band**, **128** spectra in the **mid band**, and **256** spectra in the **high band**.

ATRAC Data Reduction

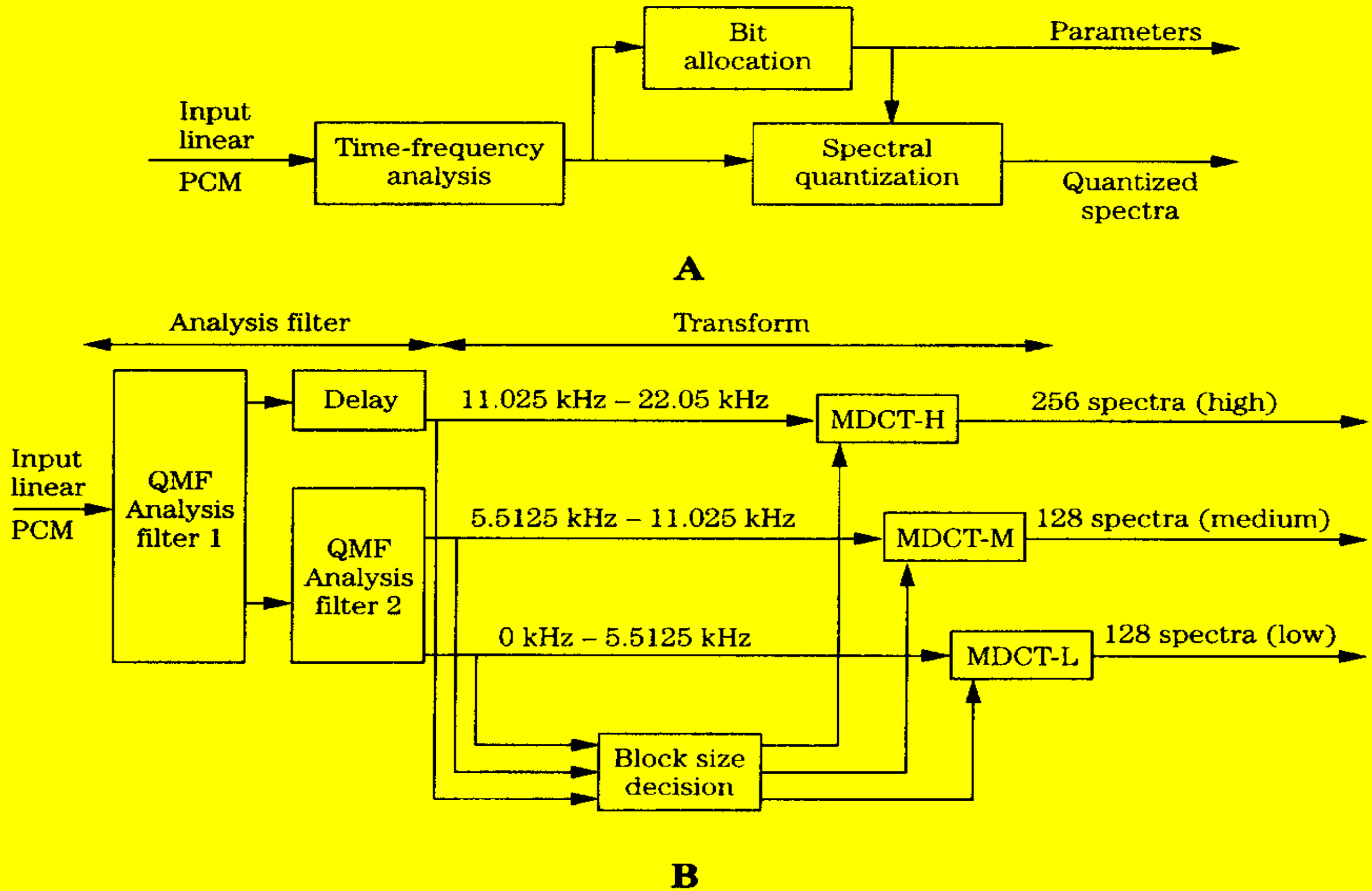


Figure 12.8 The ATRAC data-reduction algorithm is used to reduce the bit rate by coding the audio signal as spectral coefficients. A. Block diagram of an ATRAC encoder. B. Detail of time-frequency analysis block showing QMF filters and MDCT transforms used to analyze the signal.

ATRAC Data Reduction

- The ATRAC algorithm adaptively performs non-uniform time splitting, with blocks vary according to the audio contents.
- Two modes are used : **long mode** (11.6 ms in the high-, medium-, and low-frequency bands) and **short mode** (1.45 ms in the high-frequency band, and 2.9 ms in the mid- and low-frequency bands).
- The **long** block mode yields a **narrow frequency band**, and the **short** block mode yields **wider frequency bands**.
- Normally, the long mode provides good frequency resolution. However, with **transients**, **quantization noise** is spread over the entire signal block and the initial quantization noise is not masked.
- When a transient is detected the algorithm switches to the short mode.

Example of long and short MDCT block size modes

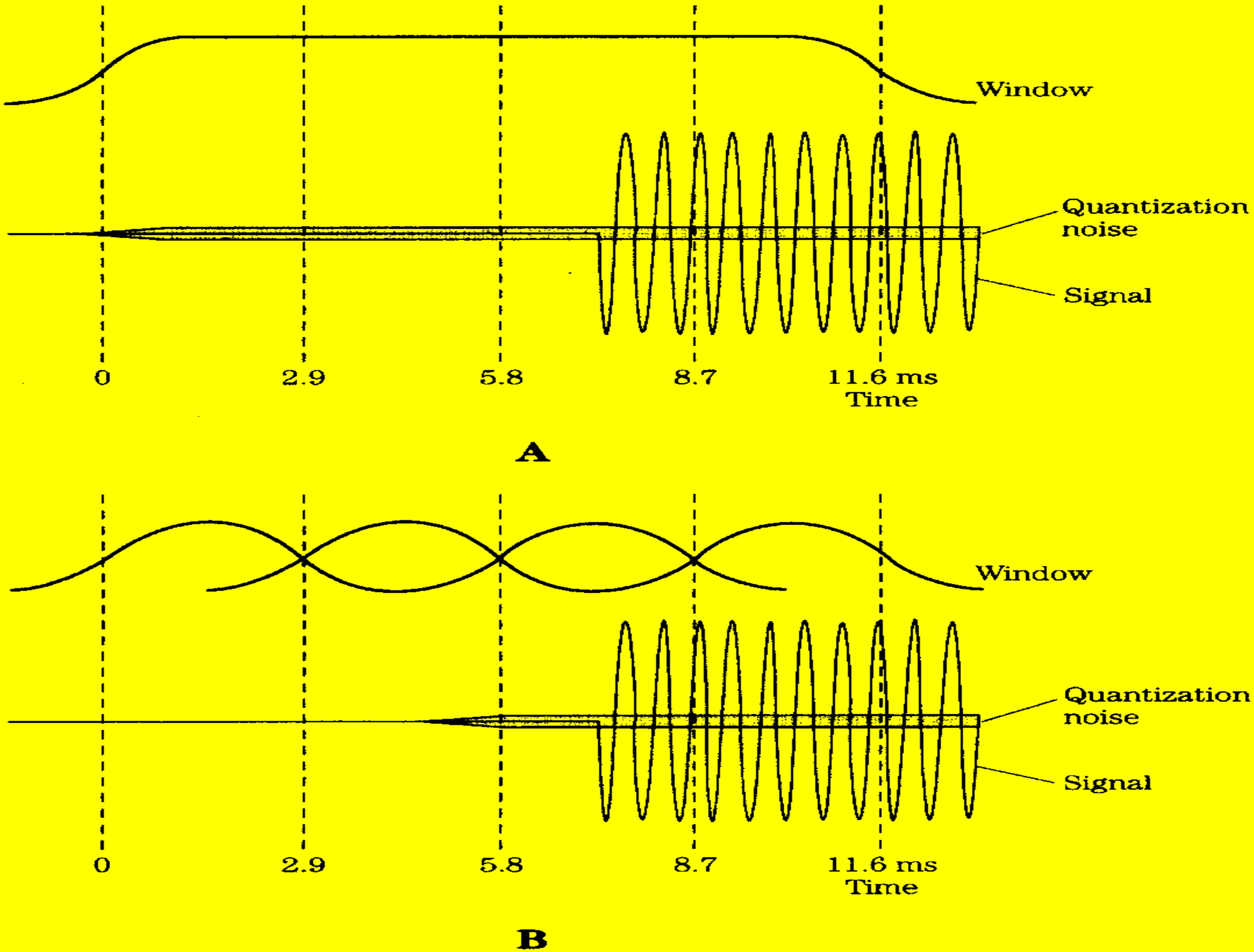


Figure 12.9 An example of long and short MDCT block size modes. In this case, a short mode is selected to overcome pre-echo artifacts. A. The long mode extends the transform over a 11.6-ms interval. B. The short mode decreases block size to 2.9 ms. (*Tsutsui, et al.*)

ATRAC Data Reduction

- The MDCT frequency domain coefficients are then grouped into **52 block floating units (BFUs);** each contains a fixed number of coefficients.
- In the **long mode**, each unit conveys **11.6 ms** of a **narrow frequency band**, and in the **short mode**, each block conveys **1.45 or 2.9 ms** of a **wider frequency band**.
- **52 non-uniform BFUs** are present across the frequency; there are **more BFUs** at **low frequencies**, and **less** at **high frequencies**.
- Lower-frequency bands are relative narrow, and high-frequency bands are wider. This widths reflect the **ear's decreasing sensitivity to high frequencies**.

Mode selection

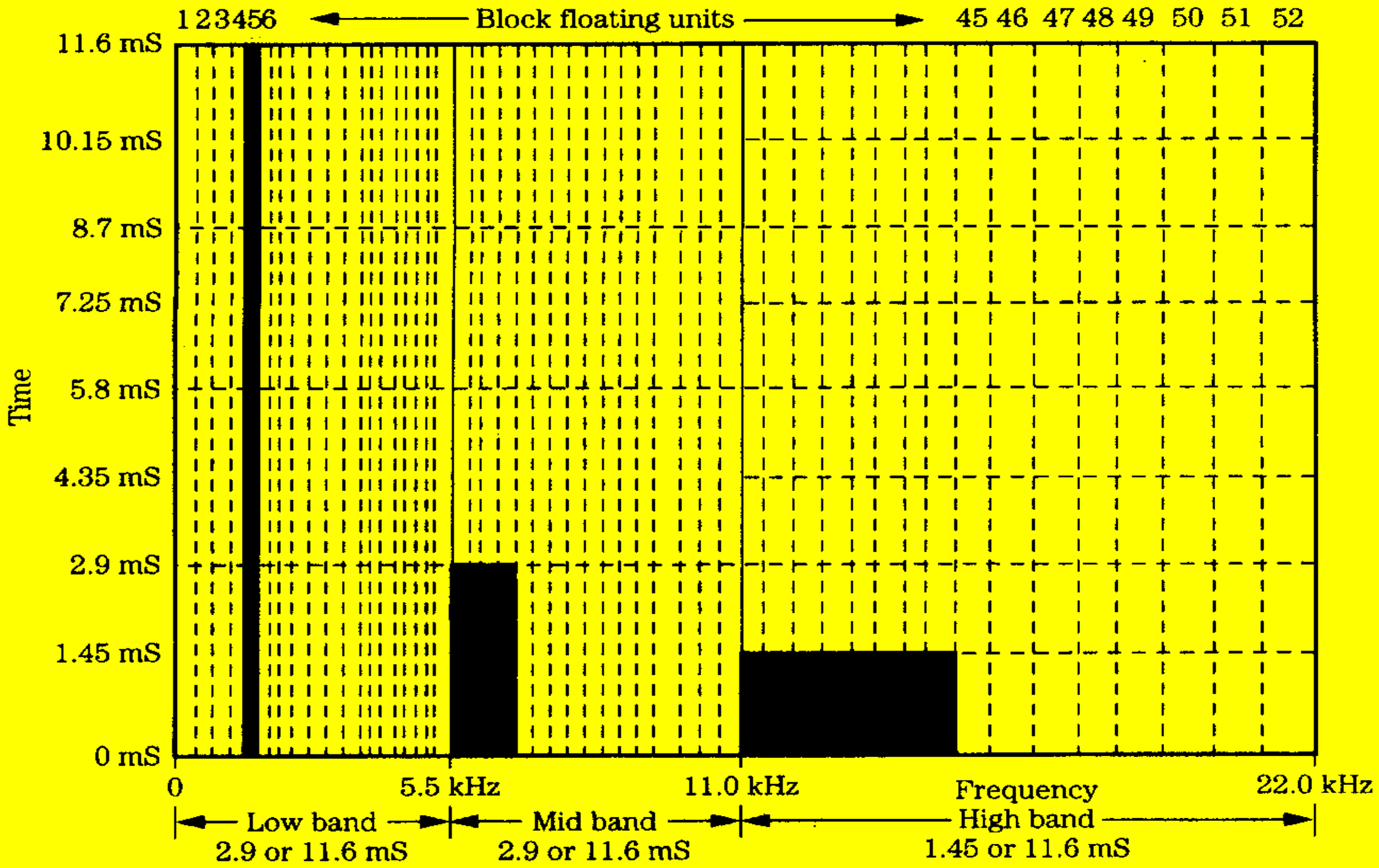
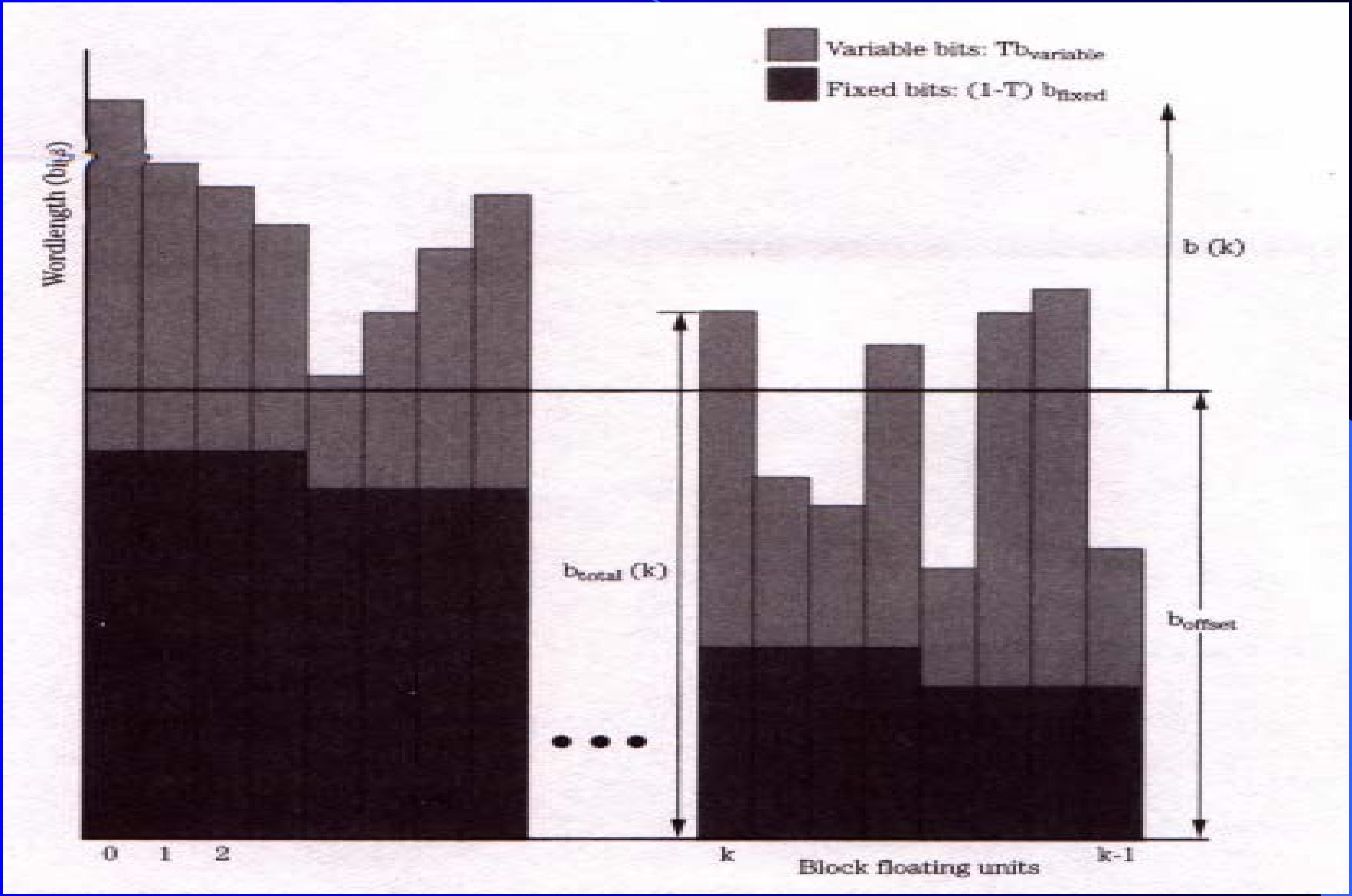


Figure 12.10 An example of mode selection in each of the three bands. A long mode has been selected in the low band, and short modes in the mid and high bands. Coefficients are grouped into 52 nonuniform BFUs across the frequency range.

ATRAC Data Reduction

- Each of the 512 spectral coefficients is **quantized** according to **scale factor** and **word length**.
- Thus the following information is coded and recorded to disc for each frame of 512 values : MDCT **block size mode** (long or short), **word length** for each BFU, **scale factor** for each BFU, and **quantized spectral coefficients**.
- The **bit allocation algorithm** operates to yield a reduced data rate; **variable bits** must be divided optimally between the block floating units.
- ATRAC does not specify an arbitrary bit allocation algorithm

ATRAC Data Reduction



ATRAC Data Reduction

- **Fixed bits** are allocated mainly to **low frequency** BFU region. **Variable bits** are assigned according to the logarithm of the **spectral coefficients** in each BFU.
- The total bit allocation b_{total} for each BFU is the **weighted sum** of the fixed bits $b_{fixed}(k)$ and the variable bits $b_{variable}(k)$ in each BFU.

$$\mathbf{b_{total}(k) = T\, b_{variable}(k) + (1-T)\, b_{fixed}(k)}$$

- The **weight T** describes the **tonality** of the signal, taking a value close to **0** for **white noise**, and a value close to **1** for **pure tones**.
- The allocation method must observe the **overall bit rate**. To maintain a fixed and limited bit rate, an **offset** $\mathbf{b_{offset}}$ is devised, and set equal for all BFUs.

ATRAC Data Reduction

- The offset is subtracted from b $_{total}$ (k) for each BFU, yielding the final bit allocation b $_{total}$ (k) :

  $$\mathbf{b_{final}\,(k) = integer\;[\,b_{total}\,(k) - b_{offset}\,]}$$

- Following ATRAC coding, **CIRC** and **EFM** operation are performed, and **compressed audio data** is stored to disc at a 44.1 kHz sampling frequency.
- Data played from a disc undergoes EFM demodulation, CIRC error correction, and ATRAC decoding.
- The ATRAC decoder essentially reverses the encoding process, performing spectral reconstruction and time-frequency synthesis.
- In addition to smaller disc size, ATRAC also permits use of a **buffer memory**, an important feature in a portable medium.

ATRAC decoder

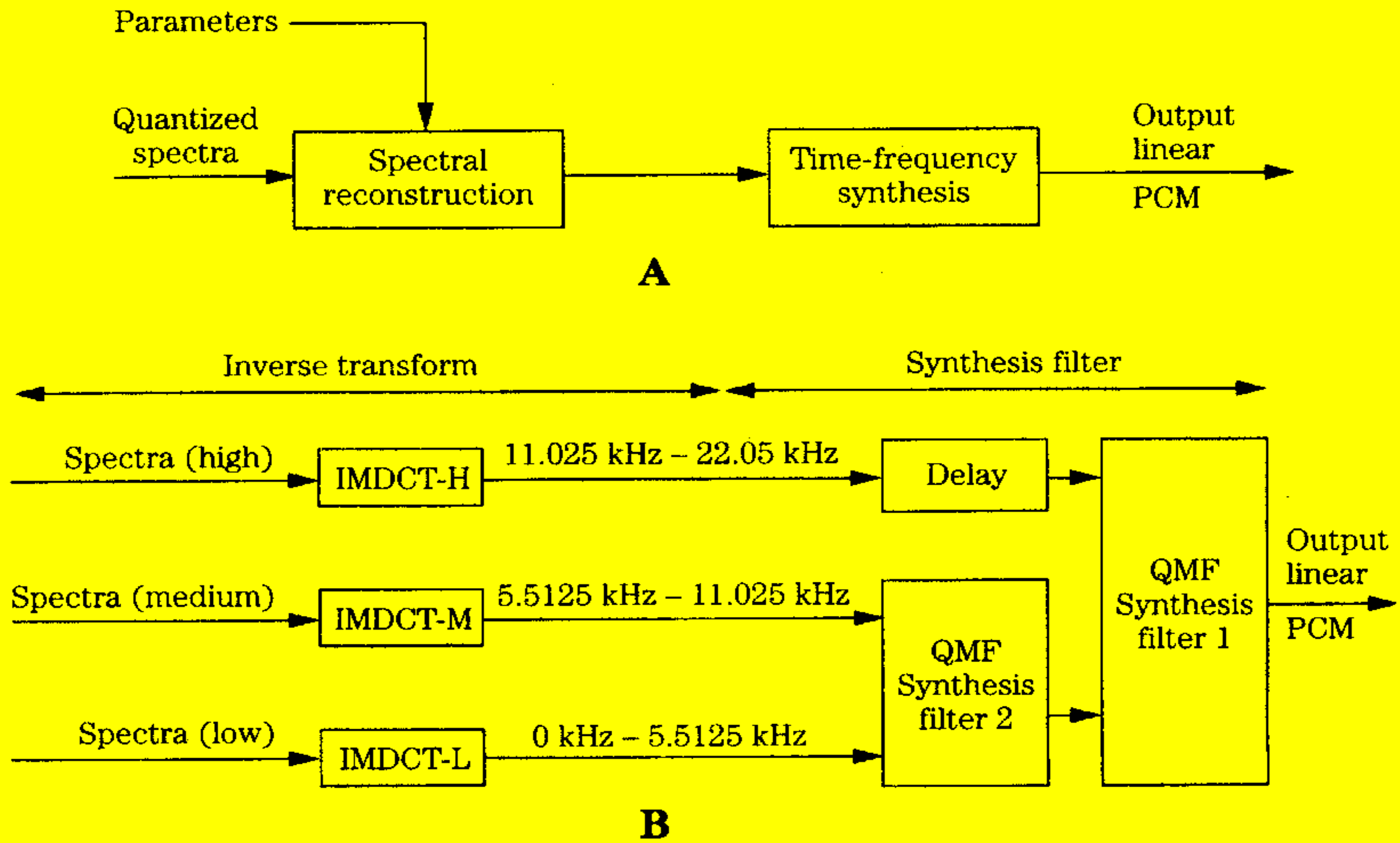


Figure 12.12 The ATRAC data reduction algorithm is used to restore the bit rate and reconstruct the signal. A. Block diagram of an ATRAC decoder. B. Detail of time-frequency synthesis block showing QMF filters and MDCT transforms used to reconstruct the signal.

Disc Mastering and Manufacture

- With proper modification, existing CD mastering systems using a ¾ **inch U-Matic tape** recorder or other source media can be used to master MDs.
- MD premastering begins with an audio source; a **format conversion process** may be used to prepare a master tape
- MD mastering proceeds similarly with CD mastering, however the PQ generator is replaced by a new address generator.
- **Recordable MDs** do not require any premastering or mastering process; however, production of any MO medium is more sophisticated than that of CDs or prerecorded MDs.
- The creation of recordable MDs begins with the injection molding of the wobble pregrooved polycarbonate substrate.

Disc Mastering and Manufacture

- **Permanent information** is stored in pits on the disc inner radius; information on **optimum laser writing power** and **disc playing time** is placed here.
- All blank MDs are identical, except for the playing time coding.
- The first dielectric, magnetic MO recording, second dielectric and aluminum layers are sputtered onto the pregrooved surface.
- These layers are covered by a protective acrylic layer.
- The completed discs are placed in double-shuttered cartridges.

Disc Mastering and Manufacture