Theory of operation of today CD systems

Rafael García
Benjamin R. Trabanco
Graduation candidates

Abstract

In this article we examine the main events that lead to the invention of the compact disc or CD, as we all call it. We consider the most important components of the playback section of the CD such as the pick-up circuit, demodulation, decoding, sample and hold circuits and the filters. A detailed examination of the CD medium and its structure is done, showing pictures to help the reader visualize the CD medium. The CD data format is also presented.

Sinopsis

En este artículo presentamos un recuento de los eventos sobresalientes que llevaron a la invención del disco compacto o CD, como comúnmente lo llamamos por sus siglas en inglés. Discutimos los principales circuitos que componen la sección de "play-back" del CD tales como el circuito de "pick-up", los circuitos de demodulación y "decoding", los circuitos de "reproduction processing" y "sample and hold" y los filtros. Se examina detalladamente el medio del CD y se presentan ilustraciones para ayudar al lector a visualizarlo. También se menciona el formato de los datos en el disco compacto.

History of the compact disc

The idea

When we first heard the beautiful sound of the compact disc (CD), we, like many other people, decided never to buy again a vinyl LP or even a magnetic tape. The idea of the CD was normally credited to a Dutch physicist named Klaas Compaan in 1969. Thanks to his idea, the evolution of the CD continued and in 1983 it led to the introduction of one of the most successful consumer products of all times: the CD digital audio system.

In 1969 Compaan thought of recording picture frames in a microscopic way on discs the size of a phonograph record. Those discs were meant for further reproduction. The images on the medium could be projected onto a screen, not only orderly but also randomly. Although his idea was removed from the results, many principles he envisioned survived the long road from research and development to the final product. His inexpensive disc stayed alive, but instead of actual visual images the disc is impressed with tiny dimple-like marks that represent digital bits and, instead of pictures, the discs can reproduce any kind of sound with the highest fidelity imaginable.

It was engineering on a grand scale: the speedy development of an infant technology, including new material for the optical discs, a solid-state laser to read digital information, and optical servomechanisms and electronics for tracking and error correction. All of these were packed into a rugged, portable, inexpensive unit.

The road to the CD

The development of the CD started at the Phillips plant in Eindhoven, the Netherlands, when Compaan told a friend and colleague, Piet Kramer, then head of the Phillips optical research laboratory, of his idea. However, the project demanded cooperation not only among different groups within

Phillips, but also between Phillips and some of its competitors. Much of the final product design took place in collaboration with Sony Corporation, which participated with Phillips in drawing up a standard CD format.

It took seven years, from 1969 to 1976, for optical-disc audio reproduction to take place. In 1970 Kramer and Compaan made a glass disc with a series of tiny black and white pictures. Each picture was 1 millimeter square and was flashed onto a screen by a conventional projector at the rate of 50 frames per second. By 1972 Kramer had decided to produce a full-scale prototype of the system comprising a disc and a player. However, they had to solve these technical problems: only several minutes of film could be carried on one disc; the material could be reproduced only by exposing a new disc, rather than by producing a master from which the replicas would in turn be sampled; and the disc rotated only six times a minute, making it highly vulnerable to small variations in speed. Another problem they encountered was that the reproduction of the video signal as a track in the disc of varying depth was not practical since it would be difficult to detect the variations in depth and to record them accurately. To avoid this problem they decided to record the information in small impressions in the disc, which Kramer called "kuilkjes", which is the Dutch word for dimples. By varying the length the dimples according to the distance between the FM signal's zeros, the signal could be reconstructed simply by detecting the dimples' edges.

The development of the laser

Although at the time gas lasers were bulky and expensive and there were doubts whether any would be cheap enough for a consumer product, Kramer and Compaan borrowed a gas laser from another lab. This helium-neon gas laser was 4 feet long and cost more than $20,000.

The laser's easily manipulated beam made devising a tracking mechanism simple. The beam was split into three; a center part with high intensity to detect the signal encoded in the dimple track, and weaker beams directed to the left and right of the track. Two photodiodes monitoring the side beams were connected into a differential circuit. If the difference between those tracking beams was zero, they were riding in the spaces between adjacent recorded tracks and the laser was on target. If the beam drifted, the differential circuit would register positive or negative, and a servomechanism took corrective action.

The gas lasers were beginning to lose ground and the solid-state lasers were emerging, but still it was a long way. Under research at Phillips, they reported that these solid-state lasers could be available by the late 1970s or early 1980s. The solid-state laser required fewer parts and would presumably bring down the system's price to levels affordable to the consumer.

By September 1971 Kramer, Compaan, and others had assembled a prototype that could read a black and white video signal off a spinning glass disc. By December they had the prototype up and running for senior managers at Phillips and by July 1972, a color prototype was shown publicly.

After examining several alternatives the engineers decided that the gallium arsenic diode laser was the only way to go. However, over the next several years, with the 1983 product introduction date looming closer, Phillips searched for a suitable laser diode, because those from other companies either proved to be too noisy or had unacceptably short lifetimes. Phillips tried to make the part in-house but was confronted by low production yields. In 1981, Sharp Corporation, not known previously for any laser expertise, unexpectedly came out with a long-life product and agreed to manufacture a laser according to Phillips' specifications.

The switch to digital

It was soon evident that FM coding was inadequate for CDs. The FM signal had about the same signal-to-noise ratio as a conventional long-playing record. Nevertheless, Lou F. Ottens, director of product development for Phillips' musical equipment division, experimented with a few analog codes and concluded that a digital code was needed. Within a few months Ottens' engineers had rigged up a digital system. Using an audio signal representative of the acoustical wave, they could sample the signal at a rate of 44,000 times per second. This rate was twice the maximum audible frequency of 20,000 Hz with some extra bandwidth for filtering and the signal was encoded as a train of square pulses. On the disc itself, they varied the dimples' length so that rising and falling edges of the pulse train corresponded to the dimples' walls. The helium-neon laser was reflected off the dimples to photodetectors connected to a digital-to-analog converter. With a 14-bit digital-to-analog converter, the best available at the time, the system's dynamic range was around 80 decibels, well above the 50 to 60 dB of the LPs.

However, there was a serious snag. The digital system proved far more sensitive to errors than the FM system, and the slightest scratch or dust particle on the disc would obliterate hundred of bits and cause a blast like cannon shot or a thunderclap. The system would require extensive decoding and error correction by hundreds of thousands of components, which at IC technology's infant state seemed likely to prove expensive.

Correcting for errors

An early dispute over the design of the error-correction circuitry focused on whether the CD should play from the disc's rim inward, or from near the spindle hole outward. Product engineers wanted the CD to play from the rim, reasoning the larger radius of the outer tracks would mean more spread out dimples there and so fewer errors in the music.

Finally they decided to have the laser pickup begin near the disc's center. To preserve the sound's quality, the motor spinning the disc would vary its speed, gradually slowing as the pickup advanced toward the rim. The linear velocity would thus remain constant and the dimples in tracks close to the center would not be crowded.

However, when it came to working out the actual error-correction code, Phillips came up against a wall despite its experience in processing. The designers at first reasoned that since the CD system had to be extremely insensitive to errors, they would use a convolution algorithm. The most rigorous error-correction algorithm available, a convolution algorithm, performs a mathematical transformation operation on a string of bits, then the same operation on a second bit in the first string, then on a string starting with the third bit, and so on, repeating the operation indefinitely. The continuous overlapping makes the algorithm extremely powerful in correcting any errors it catches.

The convolution algorithm was a great tool, but the product-engineering group still had some trouble finding an error-correction algorithm that would cover both random and burst errors. Random errors, usually only one or two bits long, were caused during the disc's processing and manufacture. Burst errors, often running to several hundred bits, came from scratches or fingerprints. It seemed that optimizing the algorithm for burst errors left it less effective against random errors, and vice versa.

Developing the disc

Even before the prototype could be readied, Phillips had to persuade a record manufacturer to develop an inexpensive disc material with the proper optical properties but not subject to warping. The obvious choice was Polygram Record Service GmbH, Hannover, West Germany, which had worked with Phillips in 50-50 joint ventures on projects such as cassette tape. It was not until 1978, when Phillips demonstrated a prototype to Polygram's management, that the disc's development began in earnest.

Polygram had the equivalent of about $150,000 and three months to develop the disc. It experimented with a plastic developed for the LaserVision, but its tendency to absorb moisture made it unsuitable for the smaller CD. Since the clear coating of plastic that protected the dimples kept moisture off one side, the disc tended to warp. With LaserVision the problem was mitigated by gluing two discs together to form one rigid double-sided disc, but that would have been too expensive for CD. Moreover, it was felt that for consumers to have to turn over the disc after each half hour of music would be unacceptable.

Polygram created a polycarbonate plastic that seemed to do the trick, it was rigid enough and did not warp. However the plastic had a troublesome tendency to alter slightly the incidental light's polarity because of birefringence, the splitting of the incident light into two rays.

Simplifying the optical system

The main objective of the optical system designers was to reduce the number of parts to cut manufacturing cost and improve reliability. The first thing to be revised was the objective lens, purchased from a microscope manufacturer. While it focused accurately, it was a general-purpose assembly and its four spherical lenses made it far too expensive.

Phillips' engineers dropped the requirement that the lens must be immune to chromatic aberration, reasoning that only one color of light would be used. Then they designed a spherical lens that would do the work of all four spherical components. Since most lenses are made by circular grinding and polishing of a rough cast, their surfaces must be a segment of a sphere. With high-precision molds, however, there is no need for grinding and polishing, and a lens can be made to any shape. Phillips laboratories were already making such high-precision molds.

To simplify the design of the servomechanism for focusing the laser and keeping it on track, Phillips engineers employed a pivoting swing-arm structure, instead of LaserVision's sled-like arrangement with the miniature optical components mounted on it and extending out over the disc. Whereas the sled configuration was more familiar, it had more parts than the swing arm and was slower to scan the disc. On the other hand, because the swing arm was more vulnerable to perturbations at resonance frequencies, it was difficult to control. After testing the swing arm, Phillips engineers decided they could stabilize the arm by limiting its size and compensating with the servomechanisms.

By substituting a semi-transparent mirror for the polarizing beam splitter, the designers eliminated the two tracker side beams and cut down still further on the number of parts. The reflected beam passing through the mirror was split by a lacquered surface and then shone on two photodiodes feeding a differential circuit connected to a servomechanism. This arrangement improved flexibility and, again, cut down on parts.

The final problem was how to keep the beam focused, to ensure that its point lay exactly on the disc's surface and that any adjustment could be made by a servomechanism. The designers employed the so-called knife-edge approach, where the focal point is sensed by a split beam focused on four photodiode detectors. These detectors are linked to a servomechanism that adjusts the focal length whenever the reflected beam falls out of focus.

Most music has pauses that last up to several seconds. With the tracking mechanism relying on a single beam focused on one track and not on dimples in tracks immediately to one side or the other, it was necessary to modulate the signal so that the laser pick-up hit dimples at regular intervals. An unmodulated digital signal would represent silence by a string of binary zeros, but an absence of dimples on the disc left the single beam with nothing to track. The engineers ran the digital signal through a modulation algorithm that ensured that the signal rose and fell regularly, no matter what the content of the audio signal.

Phillips and Sony join forces

After the first prototype was shown by the Phillips product engineering group to their managers, there was a need to enlist cooperation from such outsiders as the recording companies and even competing system manufacturers. Phillips recognized that it would be very important to join with other manufacturers to negotiate a standard before introducing the actual product. It was a controversial and risky decision because Phillips engineers felt that they clearly had the technological edge on their competitors, Matsushita, Sony, RCA and others.

Weeks later, the same prototype was flown to Japan and shown to several manufacturers. The first visitors were from Matsushita, which turned down the Phillips offer to work on a standard. Next came Akio Morita. Sony's chairman, who eventually agreed to work together with Phillips chairman Cornelius Van Der Klugt.

There were hundreds of details to be considered: the size and shape of the dimples, the data format, the configuration and size of the discs and the sampling frequency. Sony and Phillips engineers haggled for months over the exact rate. Both groups were using video recording equipment to develop their CD players. However, since television in Japan and Europe operates on different signal standards, each side wanted a rate that would be compatible with its equipment: Sony wanted 50,000 samples per second; Phillips 44,050. Finally they settled on 44,100.

The joint venture between the two manufacturers could not have been better. Both teams were leaders in their fields. Phillips had approached the project from a theoretical point of view, starting from the company's optical experience and applying that to sound recording. The Dutch team was thus farther ahead on the optical side of the design and, although Phillips had derived experience in digital coding from its work in telecommunications, Sony had been making professional audio equipment for years and brought a wealth of knowledge about digital-sampling techniques. Sony was a leader in magnetic-tape recording and the use of pulse-code modulation, digital conversion of analog signals, sampling, filtering, and other techniques that had a big impact on the CD player's electronics. Sony also had practical expertise in error correction that Phillips engineers were struggling to learn about.

The exchanges with Sony ended in 1981, after about a year of meetings. During that time, Phillips engineers say, Sony had learned a great deal about Phillips optical tracking design that had to be revealed during the error-correction work to explain some of Phillips test results. That gave away much of the lead in the product's development, but Phillips saved time in learning how to code the signal. The final product was a hybrid of the two teams' ideas.

All that was left was to work out the actual circuit design that would implement the standard format. Phillips and Sony agreed that if either designed a circuit that did not work out, the other would offer theirs, but the provision was never used. Phillips and Sony engineers had no further communication and the race was on.

Phillips engineers redesigned completely the system's electronics, made a new prototype, spent three months synchronizing and testing the prototype and then made the integrated circuits (ICs). Although the process was straightforward, Phillips had little experience in digital electronics and ICs and the work dragged. It took 18 months to reduce the jumble of boards and wires to five chips. Since Sony was an old digital hand, it was able to overcome its rival's lead in the optics, and it beat Phillips to market by a month.

Play back section of the CD

In this section we will discuss the play-back section of the CD. Figure 1 shows the block diagram of a typical CD system.

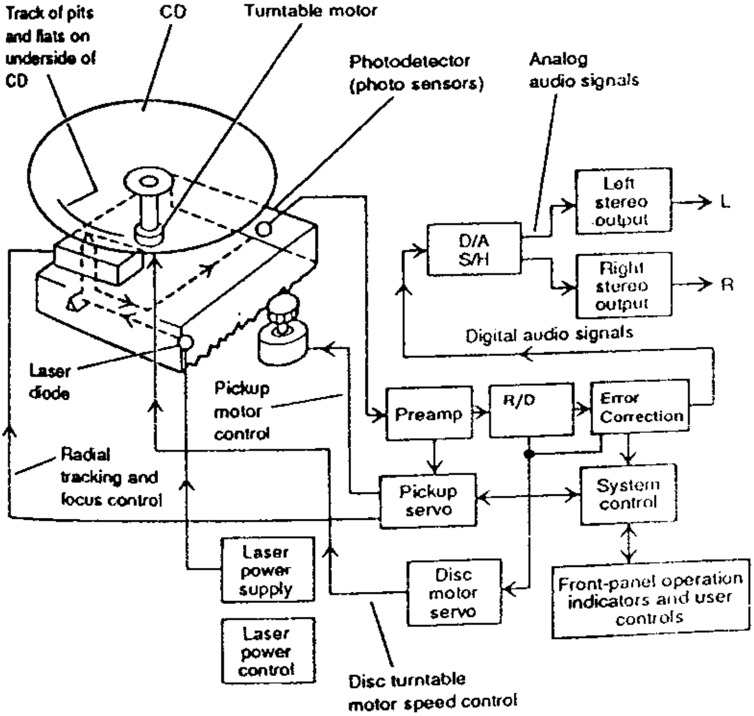

Figure 1. Block diagram of a typical CD system

The pickup

The CD uses an optical pick-up to read data from the optical medium. The optical pickup is a complex system consisting of the optoelectronic components required to focus a laser beam on the medium and track the pit data structure. The pickup transfers the encoded information from the optical disc to the player's decoding circuit. The pickup tracks the information on the disc, focuses a laser beam, and reads the information as the disc rotates. The entire lens assembly is allowed to move across the disc as directed by the tracking information taken from the disc and programming information provided by the user. The pickup must respond accurately under adverse conditions such as playing damaged and dirty discs or while experiencing vibrations or shock.

Demodulation circuit

Demodulation circuits are the first step in the reproduction of the digital audio signal, the system in which the coded waveform recorded on the disc is again converted to an analog signal. The signal derived from the reproduce head is one of very low amplitude and thus it must be amplified. This waveform is very distorted and must be processed to recover the data. Finally, the data must be synchronized and demodulated to restore the original literal data.

Decoding

CD decoding consists of EFM demodulation, frame synchronization, and error correction. The decoding system simply reverses the encoding process to extract the original audio data. The NRZI digital signal is demodulated back to NRZ signal. The synchronization word is removed from the EFM signal, and the resulting 17-bit EFM words are demodulated back to eight bits. The synchronizing word is used to control the disc rotating speed and also to indicate the beginning of frames for timing purposes within the CD player. A ROM lookup table is often used to demodulate the EFM signal. Following EFM demodulation each frame contains subcode, parity, and audio data. The data are submitted to the CIRC decoder for error detection and correction. Not all players apply the same CIRC decoding method; therefore, varying degrees of error correction can be expected. If the decoder cannot correct an error, a flag marks the uncorrected data. Interpolation and muting circuits are used to conceal uncorrectable data. Concealment circuits reconstruct the erroneous data through evaluation of the surrounding data and interpolation. If the data are uncorrectable by the CIRC decoder or unconcealable by interpolation, muting is used to prevent audible clicks. Valid data that is not flagged by the CIRC decoder passes through the concealment circuits unaltered. The subcode is removed and organized into 98-bit blocks for processing to recover the table of contents (TOC), timing, and pointing information along with CRCC error correction, addressing and control information. The data is then applied to the output electronics that consist of digital oversampling filters, digital-to-analog (D/A) converters, and anti-imaging low-pass filters.

Reproduction processing

The reproduction processing circuits are primarily concerned with minimizing the effect of data storage. Every storage medium suffers from limitations, such as mechanical variations and potential for damage of data. With analog storage the problem must generally be corrected within the medium itself. For example, to minimize wow and flutter, the turntable's speed must be kept accurate. With digital systems, because of the density of the storage, the potential for error because of storage is much greater. However, digital encoding also presents the opportunity to correct many through evaluation of the surrounding data and interpolation. If the data are uncorrectable by the CIRC decoder or unconcealable by interpolation, muting is used to prevent audible clicks. Valid data that are not flagged by the CIRC decoder pass through the concealment circuits unaltered. The subcode is removed and organized into 98-bit blocks for processing to recover the table of contents (TOC), timing, and pointing information along with CRCC error correction, addressing and control information. The data are then applied to the output electronics that consists of digital oversampling filters, digital-to-analog (D/A) converters, and anti-imaging low-pass filters.

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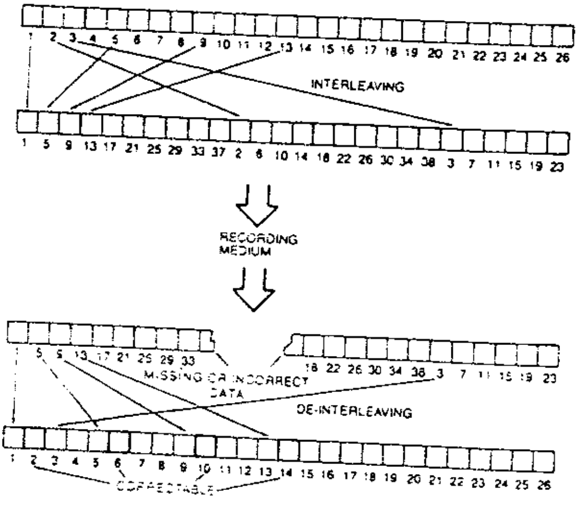


Figure 2. Interleave and de-interleave process

Description of reproduction processing circuits

The reproduction processing circuits must de-interleave the data. Before recording, the data was scattered in the bit stream to ensure that a defect in the medium would not affect too many consecutive bits. With de-interleaving, the data are again properly assembled, and bit errors caused by medium defects are now scattered through the bit stream, where they are easier to correct because of their isolation. The entire interleave and de-interleave process is shown in figure 2. The reproduction processing circuits thus accomplish buffering of the data to minimize effects of mechanical variations in the medium and to perform error correction. In addition, demultiplexing is performed to restore the parallel structure to the audio.

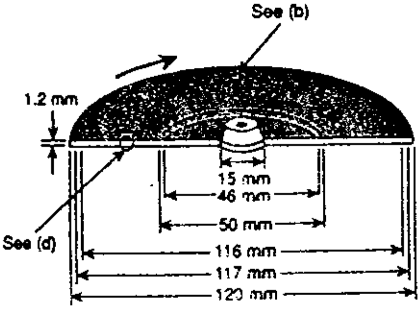
Mechanical instability in the medium transport will introduce timing errors, such as jitter, as data are read from the medium. To overcome this problem a data buffer is used. A buffer is a memory into which the data are fed, irregularly, as they arrive from the medium. However, the output of the buffer occurs at an accurately controlled rate thus ensuring precise data timing. Samples are thus assembled at the same rate at which they were taken, guaranteeing the lossless nature of time sampling.

Using redundancy techniques, such as parity and checksums, the data are checked for errors. When the parity or checksums that are calculated do not agree with those read from the medium, an error has occurred either in the audio data, or the parity and checksum data. Several methods are used to isolate the error and determine where the fault has occurred. In the case of bad audio data, error correction techniques are used to recover the correct values. By using parity bits, checksums, or redundant data, the missing values may be determined and replaced. When the error is too extensive for recovery, error compensation techniques are used to conceal the error. More simply, the last data value can be held until valid data resume. Linear interpolation is a method of calculating new data to form a bridge over the error. For larger errors, interpolation and other compensation techniques become insufficient, and error concealment becomes marginal. The presumed value differs widely from the lost original value. In extreme cases, error compensation is not sufficient, the audio signal will be switched off until valid data resume.

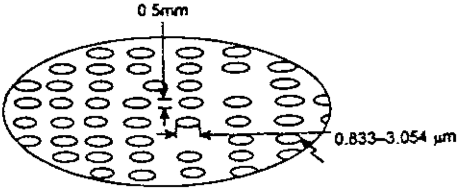
The final circuit in the reproduction processing chain is the demultiplexer. The serial bit stream now consists of the original audio data, or at least as original as the error protection circuitry has achieved. However, one remaining manipulation that must be performed on the data is to convert them to their parallel form in which they again appear as discrete words, each representing one sample value. The demultiplexer circuits accept a serial bit input, counting as the bits are clocked in. When a full word has been received, it outputs all of the bits of the entire word simultaneously, performing its task repeatedly as the data are applied.

Following the reproduction processing circuitry, the data have regained timing stability, been de-interleaved, corrected for errors incurred during storage, and demultiplexed to again form their parallel sample words. The data are then ready for digital-to-analog conversion.

The D/A converter is the most critical element in the reproduction system. Just as the analog to digital (A/D) converter largely determines the overall quality of the record system, the digital to analog converter determines how accurately the digitized signal will be restored to the analog domain. In playback-only systems, such as the CD system, the D/A converter must be carefully designed to allow stable operation under many varying conditions, especially as encountered by automobile and portable players.

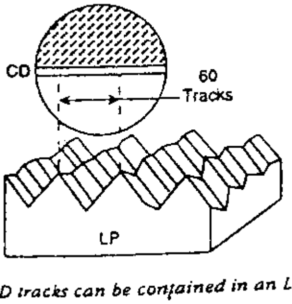


(a) Disc dimensions.



(b) Pit dimensions.

(c) Pits on the disc represent digital data via EFM modulation.



(d) Sixty CD tracks can be contained in an LP groove.

Figure 3. The CD medium

Output sample and hold circuit

Most audio digitization systems require two samples and hold circuits, one at the input to maintain the sampled analog value while the analog to digital converter performs its task, and another sample and hold circuit on the output samples and hold the signal from the digital to analog converter, primarily to remove irregular signals called switching glitches. The output sample and hold circuit is sometimes called the aperture circuit.

Output low-pass filter

The first and last circuits in a complete audio digitization system are low-pass filters, known as the anti-aliasing and anti-imaging filters, respectively, although their function is always very different. In addition to the classic analog anti-imaging filter, new digital filter design using oversampling techniques have been developed.

The CD medium

Medium

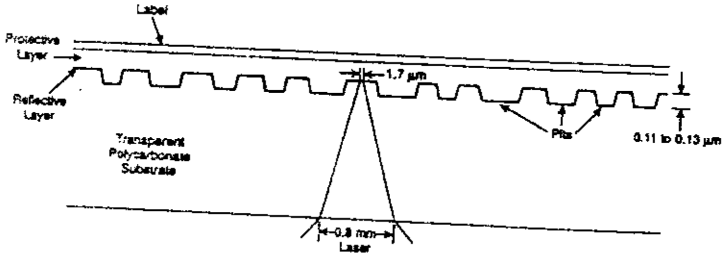
Figure 3(a) shows the dimensions of the CD. The diameter of the disc is 12 cm (4.72 in) with a thickness of approximately 1.2 mm (0.047 in). The center hole has a diameter of 15 mm (0.59 in) and allows for the disc to be placed on a CD player's spindle or motor shaft. The CD player's laser beam is guided across the disc from the inside to the outside beginning at the lead-in area and moving outward through the program area and ending at the outer edge with the lead-out area. The lead-in and lead-out areas are designated to provide information to control the player. The lead-in area contains a table of contents that provides information to the player, such as the number of musical selections as well as the starting points and duration of each selection. The lead-out area informs the player that the end of the disc has been reached. Data are recorded on a radius 35.5 mm (1.39 in) across (not including the lead-in and lead-out areas) and provide a maximum available recording time of 74 minutes and 33 seconds when CD specifications are followed. Although each particular CD rotates at a fixed, constant linear velocity (CLV), the CLV's used for different discs may vary from 1.2 m/s (42.7 in/s) to 1.4 m/s (55.1 in/s). The length of the recorder program is typically a determinant for establishing the linear velocity of a CD. A CLV of 1.4 m/s is commonly used for programs less than 60 minutes and 1.2 m/s is commonly used for longer programs. The disc's angular velocity decreases as the optical pickup moves toward the outer tracks of the discs. At a linear velocity of 1.2 m/s the angular velocity varies between 486 and 196 rpm. At 1.4 m/s the angular velocity varies between 568 and 228 rpm. Data are stored in pit formations, as shown in figure 3(b). These pits vary in length from 0.8333 to 3.054 µm depending on the encoded data and the linear velocity of the disc. The information contained in the pit structure on the disc surface is coded so that the edge of each pit represents a 1 and all spaces between the edges represent 0 as show in figure 3(c). The width and depth of the pits are approximately 0.5 and 0.11µm, respectively. The pits are placed in a spiral track with a pitch of 1.6 µm. The track runs circumferentially from the inside to the outside of the disc . The total number of spiral revolutions contained on a disc is 20,625.

Data format

A CD contains digitally encoded audio information as pits impressed into its surface. The information on the disc is read by the player's optical pickup, decoded processed, and ultimately converted into acoustical energy. The CD stores stereo audio information with provisions for four channels. The audio information is sampled at 44.1 kHz with 16 bit linear quantization. The audio output rate of the player is thus 1.41 Mb/s (44.1 kHz x 16 bits x 2 channels). The information is encoded with a Cross-Interleaved Reed-Solomon Code (CIRC) for error correction and modulated by eight to fourteen modulation (EFM) for increased information density. After the addition of the synchronization and subcode information, only about one third of the bits represent audio information.

Structure

The CD medium is a transparent polycarbonate substrate covered by a reflective material, which in turn is covered by a protective layer. The label is placed over the protective layer as shown in figure 4. The substrate allows the laser to penetrate to the reflective layer. The spot size of the laser beam is focused from an initial diameter of 0.8 mm at the disc surface to 1.7 µm at the reflective surface. Accurate control of the focusing system caused dust, scratches, or fingerprints on the surface of the disc to appear out of focus to the reading laser.



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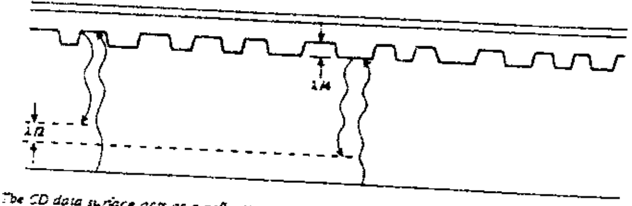

(b) The CD data surface acts as a reflective grating. Destructive interference, as a result of diffraction, conveys pit length via light reflected back into the pickup.

Figure 4. The CD cross-section

The pits appear as bumps from underneath where the laser enters the medium. The wavelength of the laser in air is 780 nm. Upon entering the substrate with a refractive index of 1.55, the wavelength is reduced to approximately 500 nm. The depth of the pits are between 110 and 130 nm and are designed to be approximately one fourth of the laser's wavelength. The pit depth of lambda/4 creates a diffraction structure such that reflected light undergoes destructive interference among the zero and first order reflected rays. This interference thus decreases the intensity of light returned to the pickup lens. The presence of pit and land areas is detected in terms of changing light intensity by photodetectors. The light signal is converted to a corresponding electrical signal by the photodetectors.

Information is stored on only one side of the CD. It is possible to store information on both sides of the disc, but due to the excessive cost of manufacturing and the added expense of extra optical hardware required for the CD player, this option is not economically feasible.