History of the Optical Disc

Paul J. Wehrenberg

American inventors including David Paul Gregg and James Russell originated some key optical storage concepts in the late 1950s and early 1960s, but initially envisioned writing with electron beams and reading by directing laser beams through the material to detectors on the other side. The concepts of a rotating disc and reflective media made optical storage a real possibility [1]. Rotating the disc and moving the optical pick-up (OPU) radially gave the required two-dimensional access to the data surface. Reflective media meant the emitters and detectors could be on the same side of the disc, greatly easing optical alignment. Burying the data surface in a transparent disc made the media robust in the hands of the consumer.

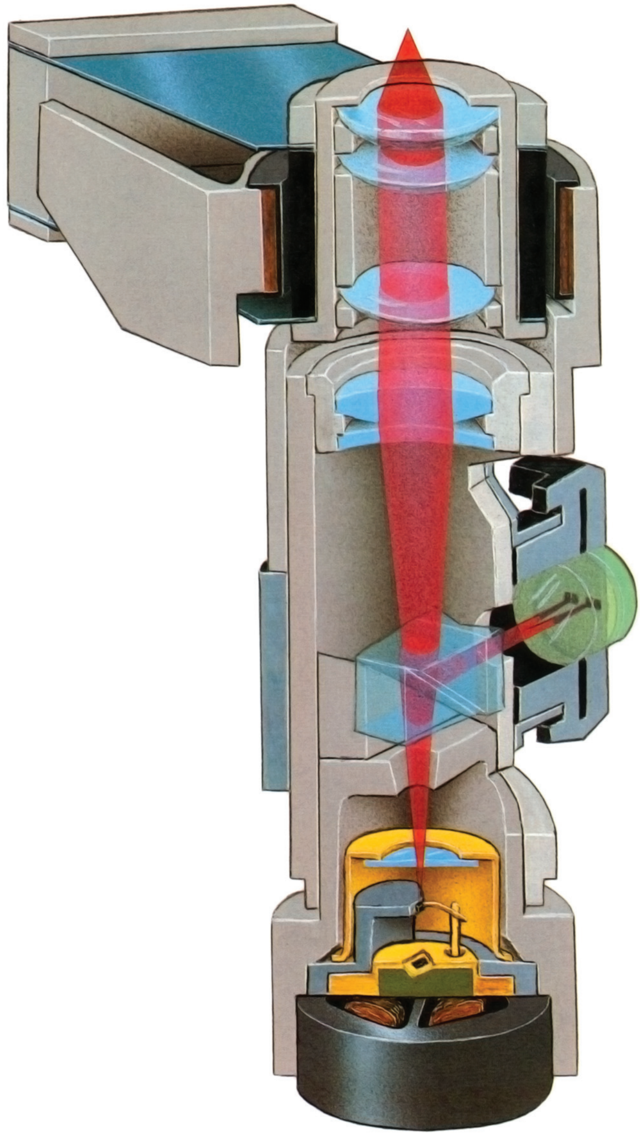
By the early 1970s, growing interest in read-only optical discs for Hollywood movie distribution led to product development. A partnership between MCA and Philips, MCA DiscoVision, introduced the first consumer laser video disc (later called Laservision) in the United States at the end of 1978. It used He–Ne gas lasers to read molded or embossed pits on a 30-cm disc, the size of a vinyl LP record. Video information was encoded as a variable distance between the edges of pits in a spiral track, yielding a frequency-modulated analog signal as the disc rotated past the laser spot.

The details of the tracking process were quite complex, and it took longer than expected to develop a reliable and low-cost process to mass produce the discs. Philips made the first fully playable disk in 1976, but it took an intense engineering effort to launch the first qualified mass production started at a factory in Blackburn, England, in 1981. The discs showed less wear than VHS tape, and image quality was better, but those advantages were not enough for Laservision to outcompete tape, which was less expensive and recordable (although most customers did not use that aspect). In the end, VHS tape thoroughly dominated consumer video distribution until the arrival of DVD in the mid-1990s.

In 1974 Philips Research Laboratories and the Philips Audio Division began developing an optical audio-disc system. Their design thinking, further detailed below, is an excellent example of system integration using the best of current technologies and additionally anticipating probable future developments in component technology, specifically digital processing power of consumer integrated circuits and wavelength reduction of solid state lasers. The project grew internally in Philips, and it was decided that analog signal recording would not work well enough and that a fully digital technique was a better approach. The magnitude of the development effort made it attractive to have partners, and after some negotiation, an agreement was reached with Sony in 1979. In-depth technical discussions were started, focusing primarily on the error-correction signal processing. The contributions from both companies resulted in a system standard which forms the physical basis of the compact disc (CD) as we know it today.

Early in the project the disc size was chosen as 120 mm and called "compact disk" because it was smaller than the 300-mm Laservision disc. They knew that the available and affordable solid state lasers for the playback devices would give them about 1 mW at approximately 800 nm, and designed the optical system accordingly (see Fig. 1) [2]. The laser beam passed through a 1.2-mm transparent substrate to read data marks embossed onto the aluminized disk surface. The embossing makes the data marks reflective phase objects.

After defining the CD-A disc standard, Philips and Sony set up a licensing organization which Philips still administers. Licensees receive a copy of the "Red Book" which details the standard and optical performance metrics. The physical standard focuses entirely on the removable optical disc. The only constraint on the disc player is that it must be able to read and play back standard-format discs. A great advantage of this sort of standard is that it allowed open-ended growth in the capabilities of disc players. For example, today's inexpensive players transfer data at 16 times the 1.41 Mb per second of initial players. The optics, servos, and electronics could handle twice that rate, but that would require spinning the polycarbonate disk at 6400 to 16,000 revolutions per minute, reaching speeds where the centrifugal force could shatter the plastic disc, a very disconcerting experience for the user.



▲ **Fig. 1.** Artist's rendering of playback optics in first Philips CD product, CD100. Size was 12 mm x 45 mm. Philips Technical Review **40**(6), 150 (1982).

Several aspects of optical disc system design are brilliant. One example is writing data tracks as a very long spiral rather than concentric circles, allowing mass-produced players to read data by following the track rather than creating it. Injection molding can replicate discs accurately and inexpensively, so this shifts the costs of achieving the required precision to the mastering machine, which is amortized over millions of replicated discs. That also allowed most players to play discs with track pitch reduced to squeeze up to 99 minutes of music onto a disc originally designed for 74 minutes. Inspired choices of eight-to-fourteen modulation coding and cross-interleaved Reed–Solomon error-correction code made the system resilient to random bit errors that if uncorrected could blow out speakers—vital because replicated disks had raw byte error rates of 10^{-4} to 10^{-5}. Establishing 2352-byte blocks for CD-audio discs left room for the error-correction codes needed to meet computer requirements of bit-error rates less than 10^{-12}, allowing development of CD-ROM for computer storage.

Writable and Re-Writable Discs

Research on write-once and rewritable optical discs accelerated in the 1970s in the U.S., Europe, and Japan as read-only discs were being developed as products. A big challenge was the limited laser power available. In France, Thomson-CSF and later Alcatel Thomson Gigadisc developed glass-substrate discs coated with thin layers of a proprietary material probably similar to nitrocellulose, plus metals including a final malleable layer of gold. It was a clever way to write data, as microscopic bumps in the gold layer, were formed by exploding the proprietary layer, but repeated laser readout deformed the gold bumps, increasing the error rate to an unacceptable level.

A more successful approach for write-once read-many-times (WORM) media was spin-coating dye-polymer mixtures onto a glass or plastic substrate. The optics in the drive are the same as for read-only discs, so the only added requirement is a more powerful delivery of peak powers of 50–100 mW peak. Philips and Sony specified the write-once CD, later called CD-R, in their 1988 Orange Book, and by the late 1990s the required lasers had become available and writing CD-R became the norm for optical drives in computer systems. The wide variety of write-once media soon became a challenge, forcing optical drive developers to develop different writing strategies for various disks and install them in player firmware.

Magneto-optic (M-O) and phase change recording were the major contenders for rewritable optical disks. Magneto-optics got off to a promising start in the early 1970s, based on synchronizing laser heating (to the Curie point) of a magnetic recording medium with modulation of the magnetic field in the heated area. The write/read heads were complex, but the media offered an essentially unlimited number of write/read cycles, so the systems could easily fit with existing computer memory management.

Phase-change media are purely optical systems based on a thin layer of a chalcogenide alloy, such as AgInSbTe or GeSbTe, which can be stable in both amorphous and microcrystalline states with different reflectivities. Illumination by a short high-energy laser pulse melts the chalcogenide layer, which cools to an amorphous state. A longer, lower-energy pulse heats the film but does not reach the melting point, causing crystallization of the amorphous layer, thus control of the laser profile rewrites the material. A great deal of research from the 1970s through the 1990s went into finding the best alloy compositions and deposition procedures.

Industry Anecdotes

The author was deeply involved in developing those systems, so he saw the dynamics that shaped their history. As a Senior Researcher in the R&D Division of Ampex Corporation in the 1970s, he was offered the opportunity to lead technical development of a either re-writable magneto-optic media or write-once media. He chose the write-once group because it seemed that write-once media were certainly as useful as ink and paper and that the dye polymer media and drives could be produced at much lower cost than the M-O media and drives. These guesses turned out to be correct in the long run. What was not realized at the time was that the changes in computer operating systems required to manage read-only and write-once media would be very slow in coming. Those file-system enhancements were not standardized and implemented until the late 1980 and 1990s, when software developers finally understood that the utility and low cost of CD-ROM, and later CD-R, made them necessary system components.

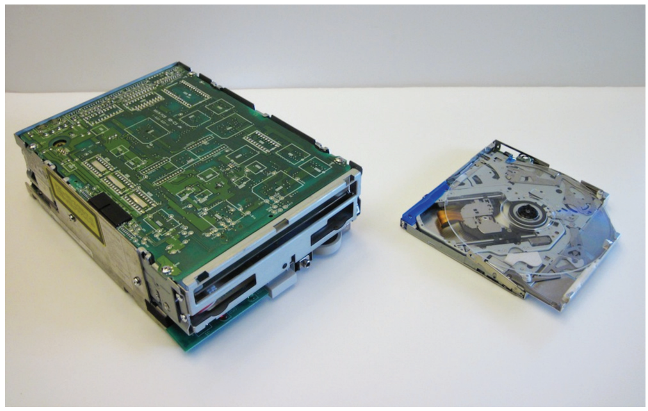
By the mid-1980s the author was on “the other side of the fence,” as Manager of Optical Storage at Apple Computer. His initial goal in joining Apple had been to develop CD-A and CD-ROM for use with Apple’s computers. Steve Jobs really liked optical storage and therefore provided good support to the CD effort. At the time, M-O developers believed the unlimited re-writeability and removability of M-O media made it more attractive than conventional magnetic hard disk drives for computer use. After Steve left Apple, rumors spread that his new company called NeXT was going to used M-O drives instead of magnetic discs in its new computer. That worried Apple management, which had great respect for Steve’s product judgment, so the author’s group began working with a major Japanese electronics company on M-O drives for Apple computers. As the possible performance and costs were learned, analysis showed that computer performance would not be adequate with only a M-O drive. The slower access time and transfer rates of M-O drives would make the computers too sluggish for the market. Subsequent developments indicate that dropping the M-O disc was the correct choice.

DVD and Blu-Ray, the 120-mm Optical Disc Drive beyond CD

When 650-nm diode lasers became available, a group including Philips, Sony, Toshiba, and Matsushita developed 120-mm dual-layer discs with capacities of nearly 5 GB on a single-layer disc and 8.5 GB on a dual-layer disc. New video codecs could generate decent NTSC/PAL video from an average bit rate of 4 Mb/s and a maximum bit rate of 11 Mb/s. The new standard also transported video data in blocks just like computer data, avoiding the differences that had existed between CD-A and CD-ROM. After resolving some "last minute" engineering issues regarding copy protection, Hollywood put their content on the new discs, and DVD became an incredibly successful consumer product for all concerned.

The DVD standard is almost purely "raising all the bars" from CDs. Shorter-wavelength lasers, better error correction codes, and more powerful VLSI chips are all evolutionary developments resulting from many person years of R&D. This history shows that evolutionary engineering developments can produce revolutionary effects. CD capacity is not large enough to support video; DVD can support video. A modern personal computer operating system will just fit on a dual-layer DVD; it would require 12 CDs or 5400 floppy disks.

Because CD usage remained quite strong, the new optical drives needed optics and electronics to support both 780 nm for CD and 650 nm for DVD. Typically the multi-wavelength optics use dichroic beamsplitters to combine optical axes through a single objective lens. In some



▲ **Fig. 2.** Twenty-year evolution of optical disc product capabilities.

Table 1. Twenty-Year Evolution of Optical Disc Product Capabilities

1988 Optical Disc Drive (AppleCD SC)
Volume of optical drive mechanism and electronics 122.2 cu"
Volume of OPU 1.5 cu"

Media types	**Maximum Read Speed**	**No Writing Capability**
CD-A	1× audio play only	
CD-ROM	2×	

2008 Optical Disc Drive (Apple Superdrive)
Volume of optical drive mechanism and electronics 11 cu"
Volume of OPU 0.3 cu"

Media types	**Max. Read Speed**	**Max. Write Speed**
CD-A	24×	
CD-ROM	24×	
CD-R	24×	24×
CD-RW	24×	16×
DVD Video one layer	8×	
DVD-Video dual layer	8×	
DVD-ROM one layer	8×	
DVD-ROM dual layer	8×	
DVD-R one layer	8×	8×
DVD-R dual layer	8×	6×
DVD+R one layer	8×	8×
DVD+R dual layer	8×	6×
DVD-RW	8×	6×
DVD+RW	8×	8×

Table 2. History of 120-mm Disc Physical Parameters by Standard

Standard Name	CD	DVD	Blu-Ray
Product Introduction	1982	1995	2003
Laser Wavelength	780 nm	650 nm	405 nm
Objective Numerical Aperture	0.5	0.6	0.85
Cover Layer Thickness	1.2 mm	0.6 mm	0.1 mm
Track Pitch	1.6 μm	0.74 μm	0.32 μm
Minimum Mark Length	0.80 μm	0.40 μm	0.15 μm
Single Layer Capacity	0.80 GB	4.7 GB	25 GB
Number of layers	1	2	2
Disc Capacity	0.74 GB	8.5 GB	50 GB

cases the "lens" is actually a dual optic with a high-numerical-aperture (NA) annular zone giving a small 650-nm spot and a smaller-NA region focusing 780 nm light to a larger spot.

Decades of research and development have dramatically reduced size and increased capabilities. Figure 2 and Tables 1 and 2 compare size and specifications of optical drives from 1988 to 2010. For demonstration, the top lid of the 2008 drive has been removed, and an unfinished 120 mm disc (metallization layer not yet applied) has been placed on the spindle. The optical pickup is visible through the still transparent disc.

The bar was raised even further in 2006 with introduction of the Blu-Ray drive product, based on the development with 405-nm lasers. Evolution in every aspect of the technology, as shown in Table 2, created a dual-layer 120-mm disc with 50-gigabyte capacity—which would have been unthinkable four decades earlier. Blu-Ray can support high definition video with four times as many pixels as NTSC/PAL video.

The future of optical disc use and development will be strongly affected by other technologies. Will consumers accept the lower-quality video distributed over the Internet or insist on the quality delivered by a 120-mm HD Blu-Ray disc? Optical discs with properly made media are as archival as silver halide, so what role will they play in archiving the data our society continues to generate at an accelerating rate?

References

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2. M. G. Carasso, J. B. H. Peek, and J. P. Sinjou, "The Compact Disc Digital Audio system," Philips Tech. Rev. **40**(6), 150–156 (1982).