A Roadmap for Optical Data S Applications

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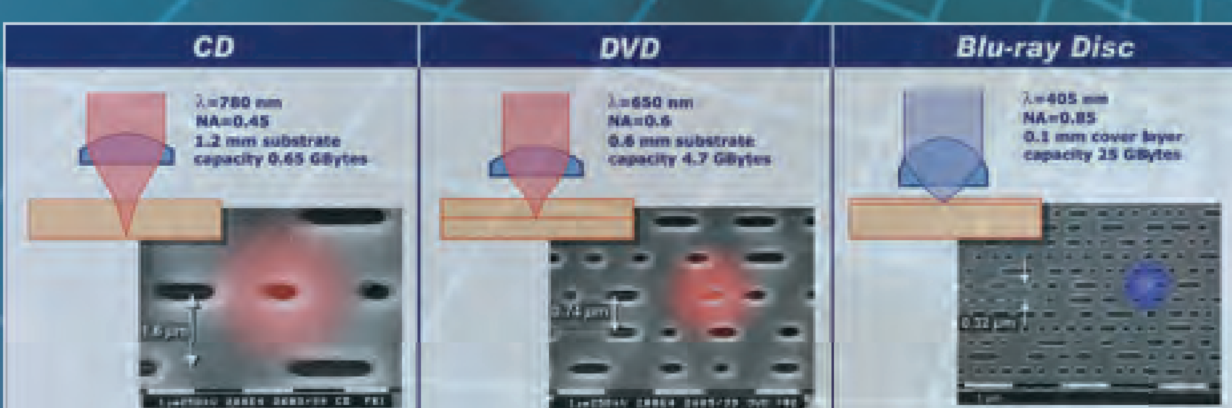


Storage

Optical products were once thought to represent the future of data storage, but their evolution has been slower than many industry experts had first anticipated. This article describes the latest progress in optical data storage applications and explains how these products will need to adapt to compete with other technologies over the next 10 years. It is based on the findings of the International Optical Data Storage Roadmap, which was recently produced by the Information Storage Industry Consortium. The Roadmap incorporates the insights of 63 invited experts representing 47 organizations from nine countries.

The mainstream optical data storage industry is now approximately two decades old. At the time of its beginnings, optical storage technology promised much higher information storage density than what was available through the incumbent magnetic tape and hard drive technologies. Experts in the field began to speculate that optical products would eventually displace magnetic devices.

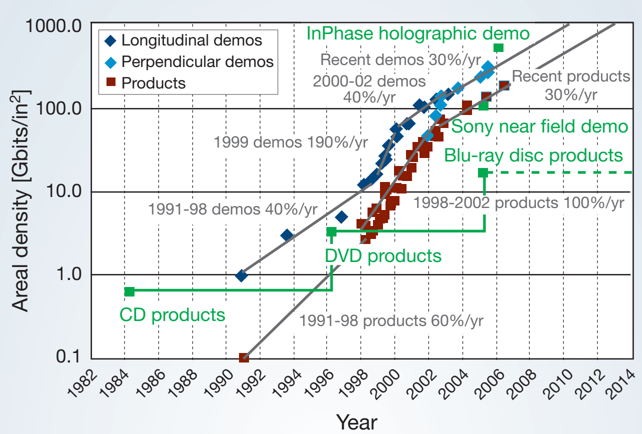
As it turned out, however, the industry evolved quite differently. Optical storage density has progressed at a much slower pace than magnetic storage density, and today's most advanced optical products have about an order-of-magnitude lower density than the leading-edge hard drive products (18 Gb/in^2 vs. 179 Gb/in^2). Still, optical products do offer the unique advantages of low-cost removable media that can either be inexpensively mass replicated or individually recorded. Rather than displacing magnetic technologies, optical data storage applications now complement and coexist with them.

The low cost and easy reproducibility of optical devices make them good candidates for information distribution and archiving applications, especially in the domain of personal computer systems. For applications in large organizations, optical technology has attained some market share for archival storage. However, that arena is largely dominated by magnetic tape. Archival applications represent a growing segment of the storage industry. This is partly because much of today's digitally created information is of fixed content (i.e., not intended to be modified). Moreover, increased regulatory influences now demand the long-term retention of many types of records.

To succeed further in this market, optical storage technology must compete effectively against magnetic tape on all fronts: cost, capacity and data transfer rate. A very significant and unresolved issue for archival applications is how to achieve longevity for data stored on various media types (traditional optical, holographic optical, magnetic tape, magnetic disk). We expect to see increasing attention directed to this issue, which must involve aspects beyond the media materials themselves, such as device- and system-level protection of data. In a recent U.S. government survey of 4,483 users, a majority considered archival longevity of more than 40 years to be important (see the graph on the left).

Because optical storage technology lags behind magnetic technologies in capacity and data transfer rate, optical applications are not used as the primary non-volatile storage technology for computer systems. They achieved some gains as a portable interchange medium between computers, but that success has been greatly eroded in the past few years by the growing presence of semiconductor flash devices. Similarly, the once-promising use of optical technologies for providing storage for personal consumer devices are now being taken over by flash memory, especially for handheld devices.

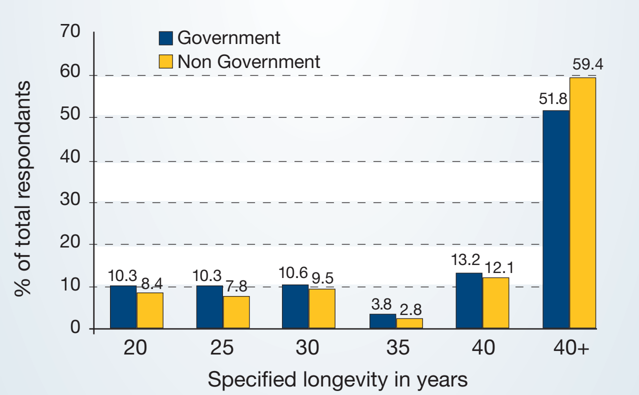
[Storage density for hard drives vs. optical data storage]



Comparison of areal density progress for hard disk drives and optical storage (green points) technologies.

Source: INSIC

[How long must data be available?]



Results of the Government Information Processing Working Group 2005 survey. More than 4,400 users were asked what they considered to be the required amount of longevity for storage media.

Source: NIST

Mainstream optical storage applications

The optical data storage industry is dominated by devices and media initially developed for consumer applications—in terms of both unit shipments and revenue. Historically, these have been the compact disk (CD), which was first developed for consumer audio, followed by the digital versatile disk (DVD), which was made for consumer video.

Each of these applications have offered read-only media (ROM) as well as recordable and rewritable media, which have found nearly ubiquitous application in personal computer systems. In many of the early systems designed for computer usage, magneto-optical (MO) technology was integrated into the application. However, MO has largely disappeared in favor of writing mechanisms using chalcogenide-based phase-change alloys or dye materials.

The progression from CD to DVD technology was accompanied by a density increase from 0.65 to 3.3 Gb/in^2. This was achieved by reducing the laser wavelength (λ) from

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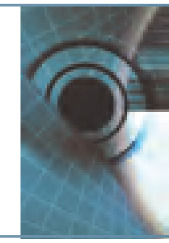


780 to 650 nm, increasing the numerical aperture (NA) of the objective lens from 0.45 to 0.60, and decreasing the media cover layer thickness from 1.2 to 0.6 mm. These changes combined to provide a reduction in the optical spot size at full width half maximum (FWHM) from 1,000 to 630 nm. With the recent advent of high definition consumer video applications, the industry has developed a third generation of consumer optical devices based on blue diode (BD) laser light sources at a wavelength of 405 nm.

Recently, two non-compatible formats have been introduced into the market: Blu-ray and high-definition (HD) DVD. Blu-ray uses NA = 0.85 and a media cover thickness of 0.1 mm, and HD DVD uses NA = 0.65 and retains the DVD media cover thickness of 0.6 mm. Both technologies offer ROM versions, as well as recordable and rewritable versions. In single-layer media, Blu-ray provides 25 GB of user capacity and HD DVD provides 15 GB. For comparison, CD and DVD provide 0.7 and 4.7 GB, respectively.

On the horizon

As capacities for optical storage media grow, data transfer rates must increase as well in order to support the newer application requirements and maintain reasonable total times for writing or reading a full disk. The transfer rate improvements have been achieved by intrinsic improvement in the original (1X) data rate with each technology generation, and also by rotating the disk faster to increase the data rate many multiples beyond 1X.

The 1X data rates for CD, DVD, Blu-ray and HD DVD are 1.2, 11, 36 and 36 Mb/sec, respectively. CD media are offered at speeds up to 52X (62 Mb/sec); DVD media are available at speeds up to 18X (198 Mb/sec); and both Blu-ray and HD DVD are available at 2X (72 Mb/sec) with expectations that future developments may reach speeds in the 8X-12X range (288-432 Mb/sec).

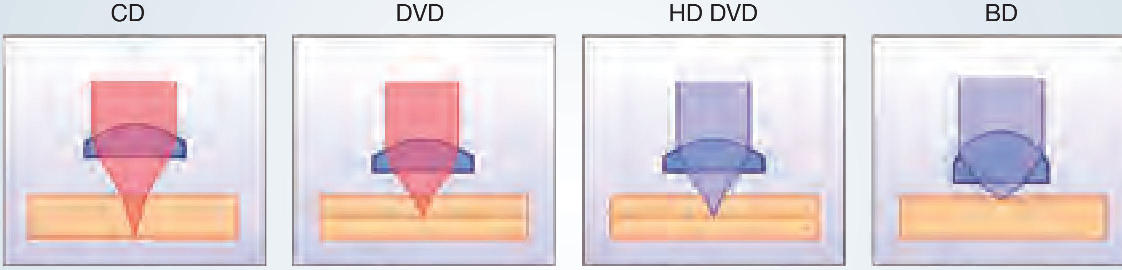
Another important goal for the future development of mainstream optical storage technologies will be to increase the number of storage layers fabricated in the disk. CD has always been a single-layer technology. DVD has been manufactured in both single-layer (4.7 GB capacity) and dual-layer (8.5 GB capacity) formats. Today, emerging BD technologies offer the dual-layer format.

Research results have already demonstrated six-layer recordable and eight-layer ROM performance. When combined with improvements in signal processing algorithms, six-layer recordable Blu-ray media could achieve a capacity of 200 GB. For optical storage to achieve significantly greater capacities than this—for example, in the 500-1,000 GB range—would require a major change of technology to one or more of the following approaches:

>> *Evanescent near fields*

Optical far-field diffraction limits the spot size of recorded and read bits, putting an upper limit on the capacity of a DVD-like disk. It will be possible to overcome this limitation with

[Key properties of CD, DVD and blue-laser recording formats]

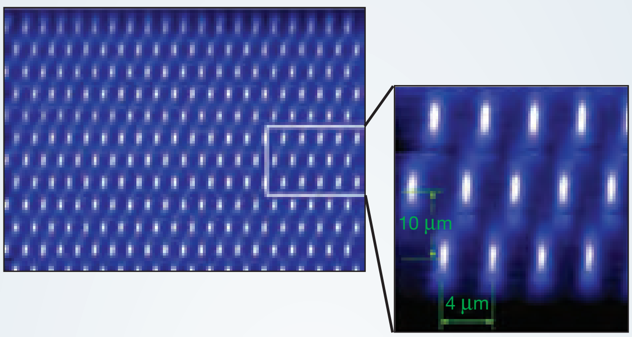


CD	DVD	HD DVD	BD
1st generation	2nd generation	3rd generation	3rd generation
Audio	SD video	HD video	HD video
0.7 GB	4.7/8.5 GB	15/20/30 GB	25/50 GB
1X: 1.2 Mb/s	1X: 11 Mb/s	1X: 36 Mb/s	1X: 36 Mb/s
λ=780 nm	λ=650 nm	λ=405 nm	λ=405 nm

Source: Philips

evanescent near-fields that can be produced by using heads that consist of a high refractive index solid immersion lens (SIL), a solid immersion mirror (SIM) or an aperture or antenna structure. The SIL, for example, can yield a numerical aperture (NA) larger than unity—which decreases the optical spot size.

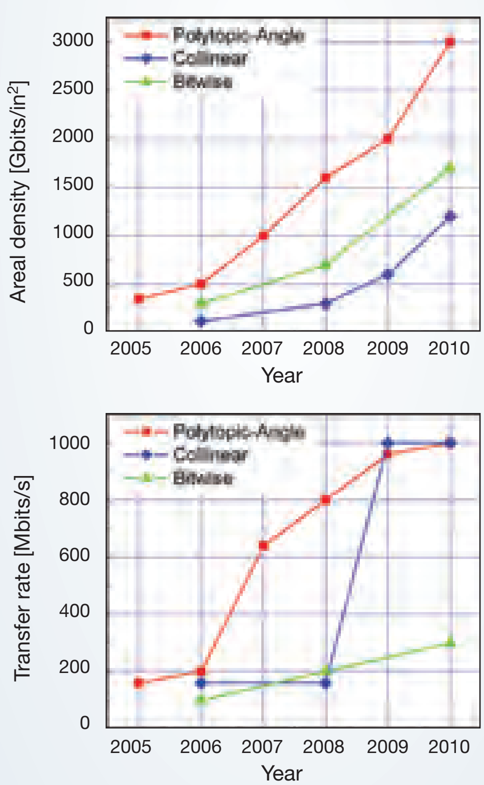
[Layers in optical storage media]



Fluorescent image of 14 layers of bits written in the volume of an Al_2O_3:C,Mg crystal. Bit separation is 4 µm in the lateral direction and 10 µm between layers.

Source: Landauer

[Density of volumetric and holographic approaches]



Projected areal density and transfer rate of bit-wise and multiplexed polytopic-angle and collinear volumetric data storage.

Source: INSIC

Researchers and engineers have invested much effort in this technique, which has demonstrated a recording density of more than 100 Gb/in^2 when operated in conjunction with novel media that have a potential capacity of up to 300 GB. Another approach to achieving a smaller spot size makes use of an aperture or pointed antenna fabricated in a thin silver or gold film. Illumination of such a structure generates highly localized surface plasmons (LSP), which are accompanied by evanescent near-fields.

These LSP have the potential of producing marks smaller than 50 nm. However, this method may suffer from throughput limitations, and thus require multiple parallel transducers. Designing read-back schemes in this case is not a straightforward problem, requiring innovative approaches.

Because they use evanescent fields, both SIL and aperture/antenna technologies require a close head-media spacing of roughly 10-25 nm. This creates significant new issues for optical data storage. In particular, such a small spacing calls removability of the disk into question, mainly because of issues associated with contamination at the surface of the disk.

>> *Super-RENS*

In another recent approach, engineers fabricate super resolution near-field structures (Super-RENS) to overcome the diffraction limit inside the media. This technique, which does not require close head-media spacing, uses metallic or metal-oxide nanostructures embedded inside the disk media. High fields excited locally around each structure generate high temperature spots in which the composition of the nanostructure is modified, resulting in a change of the effective refractive index.

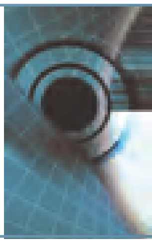
Making significant progress with this technology, researchers demonstrated 37 nm marks successfully read with about 10^{-3} bit error rates. However, both recording and readout mechanisms require further investigations.

>> *Volumetric techniques*

Instead of decreasing the mark size at the surface of a disk for increasing its capacity, one can also draw on volumetric technologies that use the bulk media of a disk. This three-dimensional approach utilizes an advantage that optical recording has over magnetic methods—namely, that recording is not confined to the surface of the disk. There are two primary directions in such volumetric technologies: (a) bit-wise and (b) holographic. In the bit-wise volumetric technique, which has been pursued by Call-Recall and Landauer (a contender for achieving the best longevity of storage media), the writing beam is focused at a prescribed depth inside the volume of the media, thus addressing a layer within which the marks are generated.

Note that this "soft" method differs from the "hard" one used in a dual-layer DVD in that the number and thickness of the layers can be tailored to specific applications, as they are not manufactured as discrete layers into the disk structure. To modify the optical properties of a mark inside the volume of the recording media, one uses a two-photon absorption process for

Rewritable materials require more research and the attainable number of layers is still an open question. Proponents of this technology aim for hundreds of layers, but practical considerations may limit this number to only several tens.



writing; this nonlinear process gives enhanced depth selectivity. The read-back is performed using fluorescence from the written mark. To increase the transfer rate, one can use parallel access to the different layers.

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>> *Holographic approaches*

Alternatively, one can use a holographic approach, where recorded data are distributed throughout the volume of a thick medium (about 1 mm). The two primary approaches to increasing capacity utilize a multiplexing approach via angle or collinear phase-conjugation. The first one, pursued by InPhase Technologies, uses polytopic multiplexing, where overlapping holograms increase the capacity of a volumetric data storage system by an order of magnitude.

By developing unique components such as a laser, spatial light modulator (SLM), detector, and drive systems, InPhase has addressed many system-level technical issues and demonstrated 515 Gb/in^2 in write-once performance. Their first write-once product, aimed at professional archival applications, is expected later this year. The product's announced specifications are a capacity of 300 GB with a transfer rate of 20 MB/s.

The InPhase product roadmap, which includes rewritable capability, is expected to extend to a capacity of 1.6 TB with a transfer rate of 120 MB/sec, as well as to provide consumer-oriented ROM devices. The second holographic method, which employs a collinear multiplexing approach, is being pursued by Optware, which seeks to address fourth-generation consumer applications and use a compact design that is backwards compatible with the DVD. The Optware SLM incorporates a concentric arrangement of a central data beam together with a peripheral reference beam. Their product roadmap extends to a capacity of 2 TB per disk.

Another emerging approach uses micro-reflector holograms, described by McLeod and co-workers and by Sony; it combines aspects of bit-wise volumetric and holographic approaches, with a potential for 20 layers totaling 500 GB capacity.

Optical storage technology and products are well established for important applications such as information publication/distribution and recording of data for long-term retention. The technology has advanced through three generations to deliver increased capacities and data transfer rates. However, magnetic tape technology is also progressing at a healthy, competitive pace, and it remains the primary competition to optical storage.

The current state-of-the-art in optical storage data is faced with a fundamental limitation imposed by far-field diffraction physics. Further advances will therefore require use of near-field evanescent radiation and/or expanding the technology from two-dimensional surface implementations to three-dimensional volumetric approaches. ◭

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