1

Introduction

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1.1 The Road to Holographic Data Storage

Digital data are ubiquitous in modern life. The capabilities of current storage technologies are continually being challenged by applications as far ranging as the distribution of content, digital video, interactive multimedia, small personal data storage devices, archiving of valuable digital assets, and downloading over high-speed networks. Current optical data storage technologies, such as the compact disk (CD), digital versatile disk (DVD), and Blu-ray disk (BD), have been widely adopted because of the ability to provide random access to data, the availability of inexpensive removable media, and the ability to rapidly replicate content (video, for example).

Traditional optical storage technologies, including CD, DVD and BD, stream data one bit at a time, and record the data on the surface of the disk-shaped media. In these technologies, the data are read back by detecting changes in the reflectivity of the small marks made on the surface of the media during recording. The traditional path for increasing optical recording density is to record smaller marks, closer together. These improvements in characteristic mark sizes and track spacing have yielded storage densities for CD, DVD, and BD of approximately 0.66, 3.2, and 17 Gb in^{-2}, respectively. BD has decreased the size of the marks to the practical limits of far field recording.

To further increase storage capacities, multi-layer disk recording is possible [1], but signal to noise losses, and reduced media manufacturing yields, make using significantly more than two layers impractical. Considerable drive technology changes, such as homodyne detection and dynamic spherical aberration compensation servo techniques [2–4], have been proposed to deal with the signal to noise losses inherent in multiple layers.

Holographic Data Storage: From Theory to Practical Systems Kevin Curtis, Lisa Dhar, Adrian Hill, William Wilson and Mark Ayres

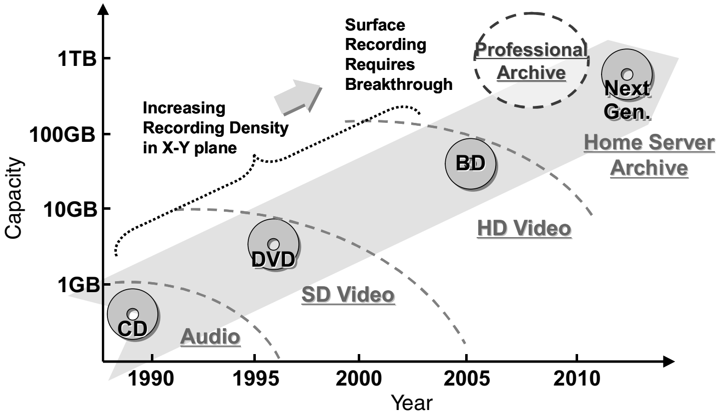

Figure 1.1 *Optical storage technology roadmap*

However, the use of multiple layers does not address the need for increased transfer rates that are required to effectively use higher disk capacities. In fact, the use of multi-layers makes increasing the transfer rate more difficult. Taking all these issues into consideration, the practical limit for the storage capacity of BD is thought to be around 100 GB, with a transfer rate of 15–20 MB s^{-1}.

Figure 1.1 shows the storage capacity of these optical technologies. The increasing difficulty in continuing to provide higher storage density and data transfer rate has triggered a search for the next generation of optical storage.

Alternative optical recording technologies, such as near field [5,6] and super resolution methods [7,8], aim to increase density by creating still smaller data marks. As the name suggests, near field methods record in the near field of the lens or aperture, so that the optical diffraction limit does not apply. Super resolution systems typically use special media structures to shorten the recorded marks. However, neither near field nor super resolution methods has shown compelling improvements over BD.

Another approach that produces multiple layers is two-photon recording in homogeneous media [9–11]. This method uses a first laser wavelength to record by producing a local perturbation in the absorption and fluorescence of the media, which introduces a small, localized index change through the Kramers–Kronig relationship [12]. A second wavelength is used to read out the data by stimulating an incoherent fluorescence at a different wavelength. The amount of fluorescence is used to determine whether a one or zero was recorded at a given location. Many layers of bits are recorded to achieve high density. Unfortunately, two-photon approaches suffer from an inherent trade-off between the cross-section of the virtual or real state (sensitivity) and the lifetime of this state (transfer rate). If the sensitivity is high enough for reasonable data density, then the transfer rate is typically low because of the lifetime of the state. In addition, in at least one example [9], the media is partially erased by each read out. Thus, two-photon techniques face both difficult media development and transfer rate or laser power issues.

With all other optical technologies facing obstacles to significant performance improvements, interest in holographic data storage has dramatically increased in recent years. For example, at the 2008 Joint International Symposium on Optical Memories and Optical Data Storage held in Hawaii, nearly half of the papers were related to holographic systems, media, components, and data channels.

1.2 Holographic Data Storage

Holographic data storage (HDS) breaks through the density limitations of conventional storage technologies by going beyond two-dimensional layered approaches, to write data in three dimensions. Before discussing page-based HDS, which is the focus of this book, we will briefly outline an alternate approach; bitwise holographic storage.

In bitwise holographic storage (also called micro-holographic storage) [13–16], multiple layers of small localized holograms are recorded at the focus of two counter-propagating beams. Each of these holograms represents a single bit that is subsequently read out by monitoring the reflectance of a single focused beam. Tracking the hologram locations through the volume in three dimensions is typically accomplished using a reference surface or part of the holograms themselves [17,18]. Bitwise holographic storage is appealing because the drive technology and components are similar to traditional optical storage, and because the media is homogenous and hence easy to manufacture. However, there are several serious drawbacks. First, it is difficult to achieve fast transfer rates. Also, it requires the invention of a material that is optically nonlinear. The technique also requires a complex servo system because the two recording beams must be dynamically focused into the same volume. Finally, the multiple layers of micro holograms cause distortion in the optical beams, which significantly limits the achievable density [19].

Unlike serial technologies (including bitwise holographic storage) which record one data bit at a time, page-wise holography records and reads over a million bits of data with a single flash of light, enabling transfer rates significantly higher than traditional optical storage devices. Page-wise HDS has demonstrated the highest storage densities (712 Gb in^{-2}) of any removable technology [20], and has a theoretically achievable density of around 40 Tb in^{-2} (see Section 2.6). High storage densities, fast transfer rates and random access, combined with durable, reliable, low cost media, make page-wise holography a compelling choice for next-generation storage and content distribution applications. As shown in Chapters 3 and 15, the flexibility of the technology allows the development of a wide variety of holographic storage products, ranging from handheld devices for consumers to storage products for the enterprise market.

1.2.1 Why Now?

Page-wise holographic storage was heavily researched in the 1960s and 1970s [21–29], but no commercial products came out of these efforts. The research was stymied by significant technical challenges, including poor media performance and a lack of input and output devices such as spatial light modulators and cameras. In the last few years, there has been a resurgence of activity and development in holographic storage, and commercial products are now within sight.

In the mid 1990s, the Defense Advanced Research Program Agency (DARPA) formed a consortium of companies and universities in the United States, led by IBM and Stanford

University, to develop high performance holographic storage systems [30–33]. The goal of the consortium was to demonstrate high density and transfer rate by developing the necessary technology and components, such as custom high speed cameras and spatial light modulators. Research in data channel modulation and detection schemes was also undertaken. Two types of storage systems were developed: one using a large crystal without mechanical motion as a recording medium, and the other using a spinning disk. The recording materials were primarily based on photorefractive crystals and on the then-available photopolymer films originally intended for display holograms [34,35]. These materials allowed basic demonstrations of HDS but did not meet the requirements for a commercial product. The consortium grew to include Polaroid (and later, Aprilis, a company spun out of Polaroid), who started developing photopolymers specifically designed for HDS [36,37]. This addition, together with the efforts of the other members, led to several significant achievements. Stanford University demonstrated high data transfer rates from a spinning disk – up to 1 GB s^{-1} [31], while IBM demonstrated storage densities of 250 Gb in^{-2} in very thick $LiNbO_3$ crystals [38].

Also in the mid 1990s, work in holographic storage began at Bell Laboratories, Lucent Technologies. Aimed at developing a suitable recording media in conjunction with a practically implement-able drive, the program targeted systems that would lead to commercially feasible products. By designing and developing both the media and drive in concert, several important technical milestones were reached: a process allowing for optically flat recording media to be fabricated using standard optical media manufacturing methods (Zerowave®) [39]; the invention of a new class of photopolymer recording material for holography (Tapestry®, two-chemistry materials) enabling both high performance and robust lifetime characteristics; and drive designs that improved signal to noise ratio and simplified servo techniques over previous systems. By 1998, data densities of 49 Gb $in.^{-2}$ were achieved in the two-chemistry materials [40]. With these technology breakthroughs in place, in 2000, Lucent Technologies spun out an independent company, InPhase Technologies®, to commercialize holographic storage systems.

InPhase has primarily focused on the development of a storage system suitable for archival applications in the professional market. The drive's architecture (see Chapter 3) was designed for ease of implementation and operation, minimizing the use of custom-developed components and ensuring environmental robustness. With this strategy, InPhase has demonstrated the highest storage density to date (712 Gb $in.^{-2}$) of any removable storage technology, media interchange between drives for the first time, and operation over a temperature range of 40°C. In addition, InPhase has partnered with some of the leading companies and organizations in the world of optical storage to productize its system, including Bayer Material Science, Hitachi Maxell Corporation, Nichia, Sanyo, Lite-On, Displaytech, Cypress, University of California at San Diego, and Carnegie Mellon University.

Also in the 2000s, companies in Japan and Korea started research into holographic storage drives and media, and several consortiums sponsored by the Japanese government were formed. Companies such as Sony and a small start-up, Optware, focused their efforts on a coaxial or collinear architecture that leverages CD and DVD technologies (this architecture is presented in detail in Chapter 3). Sony has demonstrated a storage density of 415 Gb in^{-2} [41] using collinear geometries. Sony also directed some of their efforts into bitwise holographic storage, developing methods to replicate media for read only memories (ROMs). These ROM replication efforts will be covered in Chapter 15. More recently,

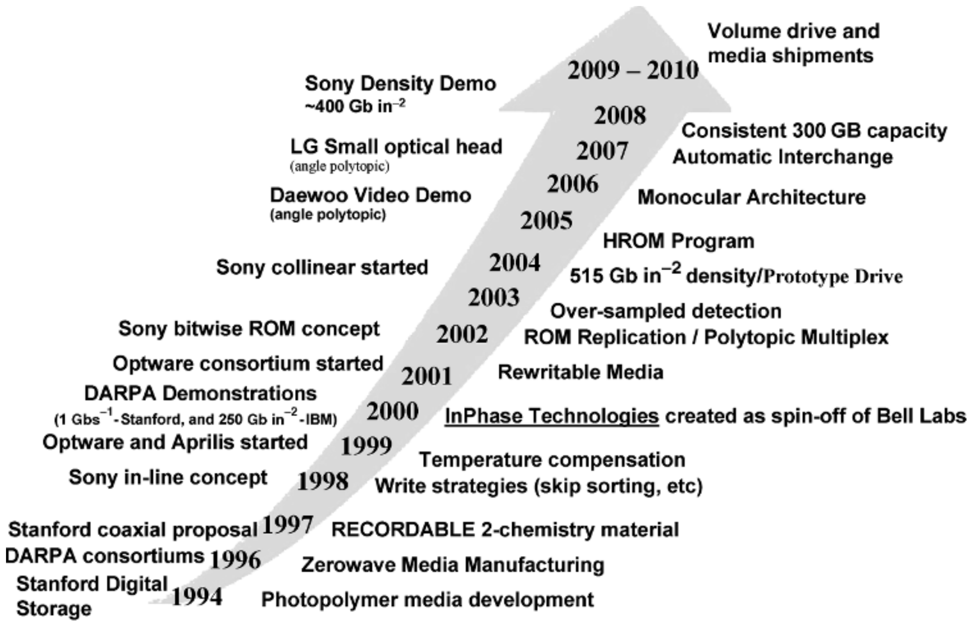

Figure 1.2 *Key holographic technology advancements of the last 15 years*

Lucky Goldstar in Korea has used the InPhase architecture to design and build a miniature optical head [25], and Korea's Daewoo has used the same InPhase architecture to achieve high speed video recording [42] and playback.

Figure 1.2 shows the highlights in holographic storage developments over the last 15 years. The right-hand side of the figure shows technical advances made by Bell Laboratories and InPhase Technologies, while those of other companies and institutions are shown on the left-hand side of the figure.

1.2.2 Focus of the Book

This book aims to present in an integrated manner, the technologies that enable practical holographic storage systems. To this end, the majority of this book will focus on the design, implementation, integration and operation of a drive and media using InPhase's drive architecture. This drive is targeted at professional archival storage applications, which require high capacity and transfer rate, media with a long archival life, and a product roadmap with performance improvements while maintaining backward read compatibility.

Focusing on a single drive architecture allows us to present a complete picture of how the underlying requirements and performance targets for holographic storage dictate the specifications for components and subsystems, and how those subsystems are developed, designed, and integrated into a complete drive.

The key features of the InPhase Architecture are (i) the optical architecture of the drive used to achieve the three-dimensional recording of the holographic data, (ii) the servo systems used to write and read the data, and (iii) the recording media which stores the holographic data. These features govern the system's performance, and sensitivity to environmental and mechanical factors.

While the focus is on a specific implementation, the principles are general – the relationships between requirements and specifications and the trade-offs between different subsystems will be common to all architectures for page-based holographic storage. To illustrate these commonalities, this book also discusses how to build on the basic technology of the professional archival drive to develop consumer products.

The optical architecture of a drive is built around a multiplexing strategy that provides the ability to overlap many holograms within the same volume of the recording medium. Many multiplexing methods such as angle, shift, wavelength, peristrophic (rotational) and correlation techniques have been investigated (see Chapter 3 for a detailed discussion), but no single multiplexing method has been able to achieve both high storage density and a robust implementation.

For example, angle multiplexing is simple to implement, provides high-speed recording and read-out, allows easy media interchange, and exhibits low sensitivity to environmental changes. However, geometrical factors ultimately limit the storage densities achievable with angle multiplexing to less than 140 Gb in^{-2} (see Section 3.3.1).

The InPhase architecture adds a new type of multiplexing, polytopic, onto angle multiplexing to mitigate the geometrical limitations on storage densities. Polytopic multiplexing maintains the speed, media interchange and robustness advantages of angle multiplexing, while allowing a more than 20-fold increase in the storage capacity of a system. In addition, by using a phase conjugate architecture with polytopic multiplexing, all the optics can be placed on one side of the media in the drive, which simplifies the optics compared with other approaches.

The InPhase drive is built around Tapestry®, a two-chemistry photopolymer recording material and media (discussed in detail in Chapter 6). The recording material is based on an interpenetrating network of two polymer systems: a cross-linked polymer that is the majority of the system and acts as the support or matrix, and a second photopolymerizable material which reacts during recording and leads to the formation of the holographic pattern. This material allows independent optimization of media performance metrics such as storage density, data transfer rate, and data lifetimes, to meet the requirements of holographic storage. In addition, the Zerowave® manufacturing process is used to fabricate inexpensive, optically flat media, using plastic substrates. This flatness improves the overall performance and signal to noise ratio (SNR) of page-based holographic systems.

Implementing the optical architecture and the recording media requires a highly interdependent effort. Aspects of the implementation such as the manufacturing of the media, the components used in the drive, the data layout format used during writing, the servo and feedback on the disk during recording and reading, and the error correction strategy, are developed by simultaneously trading off the requirements and capabilities of both the media and the drive. The servo system governs the interface between these two components.

For example, because holography records throughout the volume of the medium and the volume of the polymer-based medium can change with temperature fluctuations, a servo strategy to compensate for thermal effects is necessary. Varying the wavelength of the laser used to read out the hologram can compensate for the effects of temperature changes. The InPhase system is therefore built around a tunable laser: a coated gallium nitride laser diode, in a small, simple, stable, relatively high-power, external cavity. Also, the thermal expansion of the media can be minimized by using plastic substrates rather than glass.

Other examples, which will be expanded upon throughout this book, demonstrate the interdisciplinary development that is essential to achieving a commercially viable system:

- Writing strategies and multiplexing methods for achieving high fidelity and high-density storage in photopolymer systems.
- Parallel data channels that are significantly different from conventional serial data channels, requiring new channel detection schemes, data formatting and the use of advanced error correction codes.
- Servo methods for tracking and finding the data for the key axes such as galvo angles, wavelength, and temperature changes, allowing for fast transfer rates.
- Interchange and servo algorithms, and build processes and tools, which can be implemented in a real-world environment.

1.2.3 Other Examples of System using the InPhase Architecture

The InPhase Architecture, including media, servo, and data channel technologies, can be used to develop consumer products. The path from professional drives to consumer products using holography is similar to the path that was followed in the history of CD development. The first CD-R was a similar size to the InPhase professional drive (approximately 5.25 in $\times$ 5.25 in $\times$ 25 in), and cost US$15 000 in the 1970s (which was roughly the price of a house in Southern California at the time). Currently, the cost of a higher performance CD-R drive is around US$10, and the drive height is less than 13 mm. The following paragraphs discuss the preliminary development work on two holographic systems that are suitable for consumer markets.

The first concept is a holographic read only memory (HROM) built as a unique, optical card or chip reader that is backwards compatible with solid state memories (SSMs). In this chip reader, the slot for the replicated holographic media chip can also be used to read the SSM. InPhase has developed the process and custom tools that allow full holographic media replication in times similar to those of CD and DVD replications. The key two-step mastering process produces masters that have high diffraction efficiency and high fidelity at the high densities required for use in a fast lens-less replication process. Replicated media is read using a small HROM prototype reader. Chapter 15 describes this concept and implementation in detail.

Working with Hitachi, InPhase has also developed a consumer optical storage system; an implementation of the InPhase Architecture that is backwards compatible with Blu-ray. The system uses a monocular architecture that passes both the data beam and the plane wave reference through the same high numerical aperture lens. The media uses a grating to enable phase conjugate read-out, which allows for a slim height (12.7 mm) using appropriately sized components. With the already demonstrated density of 712 Gb in.$^{-2}$, a 120 mm disk can store $>$500 GB of user data, with a transfer rate of 100 MB s^{-1} or more. Chapter 3 introduces the monocular concept and Chapter 4 specifies the required components needed to implement an inexpensive, slim height drive.

1.3 Holographic Data Storage Markets

1.3.1 Professional Archival Storage

The first market for HDS is professional archival storage – the long term storage of digital assets. Demand for long term archival storage and fast data access is being driven by regulatory compliance requirements, an increased volume of fixed-content data, surveillance and security systems, and the explosion of rich media applications. Storage for these archive and data distribution markets is primarily based on removable media.

'Long term' archiving means being able to store data for several decades without the need to refresh or migrate them (data migration is typical for tape-based storage). These time periods are considerably longer than the 3–7 years commonly required for transaction data. In 2005, the United States Government Information Preservation Working Group (GIPWoG) surveyed users about their longevity requirements for archival storage. Partial results from the survey are summarized in Figure 1.3. Close to 60% of the 4483 respondents indicated an archival life requirement of over 40 years for their data. Further details are available in the INSIC International Optical Data Storage Roadmap [43].

Regulatory compliance legislation, passed in the US in the early 2000s, has raised the importance of data protection and archiving. The intent of many of the regulations is to protect data that may be of value in litigation. The write once aspect of holographic write once read many (WORM) media is a good fit for this requirement. The legislation also mandates that data must be archived for periods of up to decades. These compliance regulations impact a broad range of industries such as financial services, healthcare,

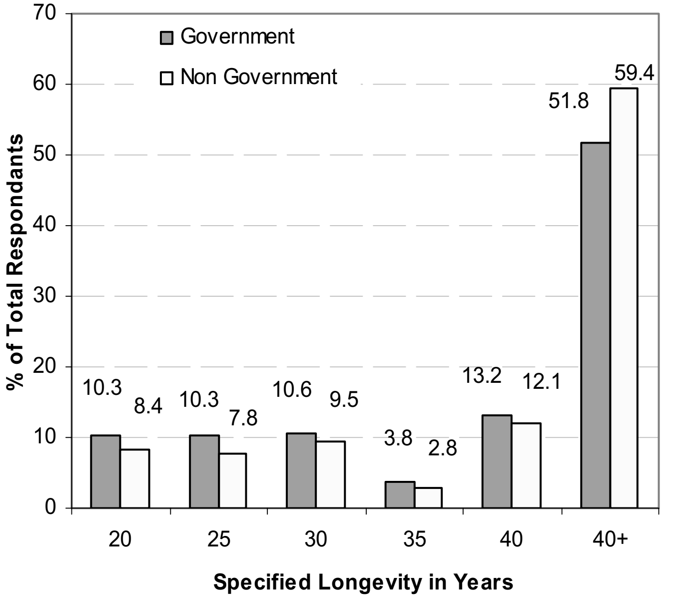

Figure 1.3 Results of a 2005 user survey by the US Government GIPWoG group. There is a strong preference for 40+ year longevity for archival data

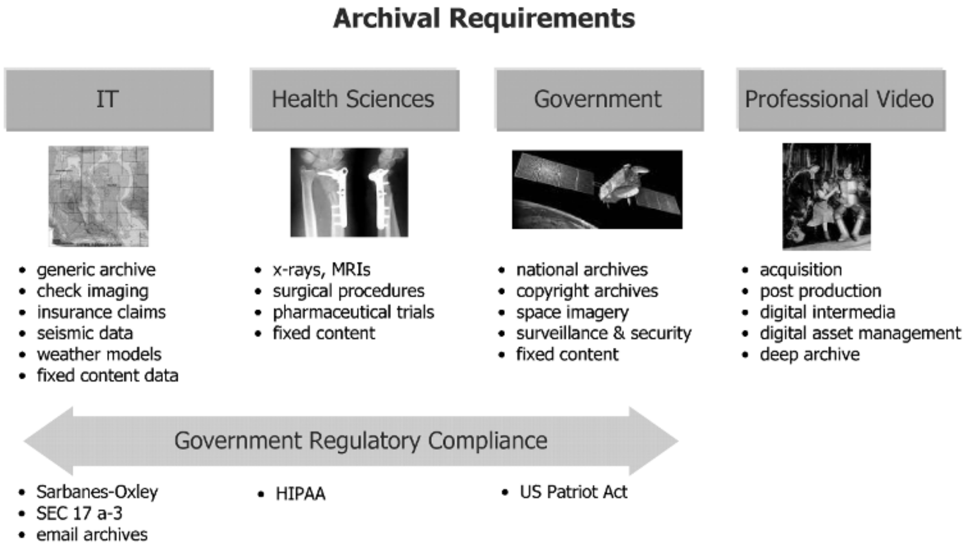

Figure 1.4 *Professional archival markets overview*

pharmaceuticals, and government data, as well as email archives in all industries. Data archiving has gone from being an irritant to becoming a major application, with additional requirements to protect the data from alteration and unauthorized access. Significant fines have been levied against companies that fail to comply. Figure 1.4 summarizes several important archival markets and the regulations that are driving some of them.

Rich media video and audio applications have emerged as another new market that has very long archive requirements. Content in the incumbent analog video and audio technologies is being migrated to digital formats, to leverage the lower cost of managing digital workflow from content acquisition, to post production, distribution, and archiving. The market is also expanding because high definition (HD) formats generate even more data than the older standard definition formats. For example, 1 s of video may generate 12 MB of data. Often over 100 times more video footage may be shot than is actually distributed, so a 30 s commercial or a 2 h movie will generate terabytes of content. The high cost of acquisition and the revenue generating nature of the content, mean that archive expectations are ‘forever’.

Historically, magnetic tape has been the predominant technology for back-up and archive applications because of its high capacity, high transfer rate, and low cost media. However, when archiving data for more than a few years, data tapes are often stored in a temperature and humidity controlled environment, which is expensive to construct and maintain. If the stored data are especially valuable, it will be migrated to new tapes anywhere from once a year to once every 7 years, which incurs further labor and media costs. In addition to its reputation as an unreliable data recovery format, tape has long access times to data because of the need to rewind or advance the tape spool. In spite of these problems, until the advent of holographic storage, no other technology has been compelling enough to displace tape.

Conventional optical drives such as magneto-optical drives, and to some extent DVDs, have also been used in the IT sector for digitally archiving items such as medical records, bank check images, and telecommunications logs. The primary need in these applications is the write once feature of optical technology which protects the data from being erased or altered. Customers in this market segment require high reliability, stable and long-lived media and multi-generational backward read compatibility. The random access to data, and low cost unalterable WORM media, also provide advantages over tape. However, the principal challenge to technology is its limited capacity and slow transfer rates, even when the latest generation – Blu-ray – is considered.

Hard disk RAID arrays have dramatically impacted both back-up and high access, short term (1–3 years) archive markets. These arrays have tremendous performance and have benefited from increases in disk drive capacity. However, disk drives have limited lifetimes (3–5 years) if they are kept spinning or are spun up at least every few weeks. Thus, RAID arrays have been limited to use for short term, high access, fixed content and back-up markets. For long term archive (over 7 years) these solutions are very expensive to buy, maintain, power, and keep cooled.

Several companies have implemented disk-to-disk-to-tape systems to address the issues of limited accessibility and recoverability associated with a pure tape back-up and archive strategy. However, the issue of long term archiving remains a problem with these hybrid solutions because hard drives are expensive for storing infrequently accessed data, and tape remains a problematic data recovery medium.

Holographic storage offers a compelling alternative because the capacity and transfer rate are competitive with tape, with the additional benefit of random access in a disk format. The media cost is lower than for the new blue laser optical formats, and has the advantage of a 50 year media archive life in unalterable WORM media.

Holographic technologies offer improvements in the performance and cost curves of storage that make increasingly large amounts of data accessible to users, while reducing the total cost of storing the data.

The value proposition for holographic data storage products includes:

- Highest performance for removable storage, which combines a demonstrated data density of over 712 Gb in^{-2}, random access (around 250 ms), and transfer rates capable of exceeding 120 MB s^{-1}.
- A 50+ year media archive life, requiring no special handling, refreshing or environmental controls; and no wear from media contact with a read/write head.
- Near-line random access to content, making petabytes of data almost instantly accessible.
- Smaller media format with higher density per cubic foot.
- Lowest cost per gigabyte for professional grade media, making archiving affordable for terabytes to exabytes of data.
- Improved data protection with a true (intrinsic) WORM media format that ensures that the data retains its original state.
- Lowest total cost of ownership, resulting from low media costs; reduced frequency of media migration; smaller media size (which reduces data center floor space requirements); and power savings, achieved by decreasing the use of hard disk drives to store infrequently accessed data.

HDS has a sustainable advantage over other technologies, with a roadmap that allows drive functionality to improve over time while maintaining backwards compatibility. The current InPhase Technologies roadmap has the second generation drive (800 GB capacity, with

80 MB s^{-1} transfer rate) appearing 2 years after the 300 GB drive, and the third generation (1.6 TB capacity and 120 MB s^{-1}) appearing a further 2 years later. This is a faster growth curve than for tape, hard disk or SSM technologies.

Magnetic tape, hard disk, and CD/DVD/Blu-ray are the current competitors for HDS in the archive market. Media reliability is the major problem with tape. Performance is the major limitation for traditional optical storage, while lifetime, cost, and power usage are the issues with standard hard disk. Figure 1.5 summarizes the pros and cons for each technology.

According to IDC, the OEM market size for archive drives and media will be US$17.5 billion in 2010.

1.3.2 Consumer Applications

Removable storage for consumer applications is largely dependent on optical disk and solid state memory technologies to satisfy the ever-increasing demands for distribution, recording, and storage. For distribution, archiving, and video recording, traditional optical storage is by far the predominant removable storage technology in use today. Blu-ray has pushed the limits of capacity and transfer rate of surface recording technologies, and next generation removable products require densities and transfer rates that cannot be provided by incremental improvements of these technologies.

 Tape		 Hard Drives		 CD/DVD	
Pros	Cons	Pros	Cons	Pros	Cons
• High Capacity • High Transfer Rate • Low Cost Media	• Media Reliability • High Media Maintenance $ • Slow Data Access • Not True WORM	• High Capacity • Low Cost / GB for device • Easy to use • Random Access to Data	• High Power Usage • Device Life 3-5 years • Not Archival Format	• Good Media Archive Life • Low Cost • True WORM Format	• Low Capacity • Low Transfer Rate

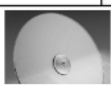 Holographic Technology Benefits	
Pros	Cons
• High Capacity competes with tape and hard drives, 6X more capacity than BD • Media Archive life +50 years vs 3-7 years for tape and hard drives • Random Access to data; milliseconds to file vs minutes for tape • True WORM Format Protects Archive Data • Low $/GB media competitive against tape and existing optical • Transfer rate much higher than existing optical • Low power requirements	• New technology • WORM only format at Introduction

Figure 1.5 *Competing technology options for archival storage applications*

The initial consumer markets for HDS will likely leverage its removability, inexpensive media and replication, and long archival life, for home archiving and content distribution. As consumers produce more digital content in the form of movies and pictures, the need to archive them effectively will become painfully clear. This market shares many of the requirements of professional or enterprise archiving, where the content is expected to be preserved for a person's lifetime.

InPhase has developed two concepts for consumer markets that leverage the technology developed for the professional drive. The first concept is a holographic ROM with high speed, full media replication for content distribution. The reader and media card are the same size as SSM formats to allow the drive to read both SSM media and holographic media with replicated content. Prototype replication equipment and a small prototype reader have been developed (see Chapter 15). While SSM has significant advantages for mobile applications, it does not have an easy, fast, and inexpensive method to distribute content. The InPhase Technologies reader and low cost replicated media is intended to complement SSM in applications where content distribution is required, for example, for games, software, maps, videos, movies, and so on.

The second concept, called the monocular architecture, implements a slim height, optical drive that is backwards compatible with Blu-ray (see Chapter 3) and would be used for both home archive and content distribution. This uses a Blu-ray like 0.85 numerical aperture lens to introduce both reference and data beams to the media.

For the consumer market, HDS provides:

- Highest performance removable storage **with** highest capacity (500 GB–2 TB per disk), random access ($\sim$250 ms), and highest transfer rates ($>$50 MB s^{-1}).
- Rugged, able to withstand on-the-go use because there is no contact between media and head.
- Low power, and low noise because the media does not rotate.
- Low cost, small size drives and media for use in mobile applications.
- Long archival media life requiring no special handling or environmental controls.
- Random access to content.
- High-speed and low-cost replication for physical content distribution.
- Unique formats with a card reader that is compatible with SSM.
- Low cost media due to plastic substrates and photopolymer.

Drives based on the monocular architecture can be the next generation of optical storage (Figure 1.1) because of the ability to efficiently replicate disks, backward compatibility with Blu-ray (BD), the slim height of the drive, and the advent of inexpensive media. While a version of BD with 50 GB per disk (2 layers) is available in Japan, it is possible that a 100 GB BD will be commercialized eventually. Significant modifications to the Blu-ray drive will be required to compensate for the change in focal depth inside the media, and to increase the SNR and light throughput. HDS will allow the next step up in both capacity and transfer rate for optical technology, which will allow for effective home archiving, as well as distribution of three-dimensional, ultra high resolution, or user-controlled content.

Figure 1.6 compares the prevalent storage technologies for consumer archive and content distribution. Flash or SSM is, and will remain, dominant for mobile applications because of its power, robustness, and size advantages. However, it does not support an inexpensive method to physically distribute content. Hard drives are dominant in computers, but are not

Flash		Hard drives		CD/DVD	
					
Pros	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
• Small size • Robust • Ease of use	• Low capacity • High $/GB • Slow replication	• High capacity • Low $/GB	• High power usage • Shock sensitive	• Low $/GB • Low cost replication • Standard for distribution	• 120 mm • Large device

Holographic technology potential	
Pros	**Cons**
• High data density • Flexible formats • Low $/GB media • Low cost / high speed replication • Low power usage	• New technology • Need new standard

Figure 1.6 *Advantages and disadvantages of various technologies for consumers*

appropriate for these two initial applications. BD/DVD/CD are dominant in content distribution but have reached, or nearly reached, the end of their technology roadmaps, and cannot supply the next increase in performance.

IDC estimates that the consumer market for drives and media in these technologies will be around US$32 billion in 2010. The fraction of the market for distribution and archival (all optical and some SSM) applications is estimated from IDC numbers at around US$18 billion for drives and media. Clearly, the current market potential is very large, and expected to grow significantly.

Advances in network technology are expected to significantly affect the content distribution market. As connection speeds increase, Internet or pay for view services will continue to be a force in content distribution to the home. While this trend is likely to make the home archival market segment even better for holographic technology (because this content is not delivered in a form that is already archived like an optical disk), it does represent competition to physical distribution. Even if the content is not user generated, if the data will be owned rather than rented, some archive storage must be used for storing the downloaded material.

Physical distribution has some advantages over network distribution in that the content is already archived, can be taken anywhere, can be more securely distributed, and large content can be distributed easily. However, renting content over the network is easier than renting physical media, and you do not need to worry about keeping it. The market will most likely see both physical and network distribution thrive, and even as distribution to mobile devices becomes available, physical distribution will continue to be an important part of the huge and growing market.

In Chapter 16, we will return to this topic and speculate on how the technology may evolve, and which other markets may then open up for holographic technology.

1.4 Summary

This book coincides with the commercialization of the first HDS product. The drive has 300 GB capacity, fast transfer rates through standard computer interfaces and operates over wide environmental conditions. However, this is the just the first step for the technology, and much more can be done. The performance of both media and drive can be dramatically improved. New technology can be developed that simplifies the drive construction, improves performance, and lowers cost. The technology will also be applied to the consumer market.

The last book published on HDS is now 10 years old, and out of print [44]. While it was an excellent introduction, it was a snapshot of the status of a number of research groups at that time. This book describes the advances made since that time and details the technology required to make data storage products using holography. It is hoped that by understanding this technology, others will be able to use it to develop their own holographic storage products.

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