Holographic Data Storage

From Theory to Practical Systems

Kevin Curtis, Lisa Dhar, Adrian Hill,
William Wilson and Mark Ayres

InPhase Technologies, Longmont, CO, USA

WILEY

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Foreword

The modern field of nonvolatile digital information storage is a bit more than a half-century old. During its history, the field has seen a small handful of technologies (magnetic tape, magnetic hard disk, magnetic flexible disk, consumer-derived optical disk) take root as 'mainstream'. These technologies have persisted in the market place from their earliest introduction until today, experiencing commercial success for several decades or longer. A few other digital storage technologies have emerged and been successfully commercialized in less broad based applications (e.g. magnetic drums, optical cards, magneto-optical disk) and, typically, their success has been of shorter duration. A third, quite numerous, category of storage technologies involves new approaches that have not yet achieved commercial success. The subject of this book, holographic data storage, is in this third category.

Among the many examples of promising storage technologies that have been worked on over the past 50 years, holographic storage offers a unique combination of desirable attributes: extremely high density of stored information, a disk format capable of rapid random access, and a removable nonvolatile storage medium that may be inexpensively manufactured. While these attributes are simple to discuss in general, putting them all together in a practical and reliable storage system represents a herculean engineering task. This is exactly what InPhase Technologies has accomplished, and what the company's contributors describe in detail in this book.

As the authors point out in the Introduction, with other optical storage technologies facing obstacles to significant performance improvements, interest in holographic data storage has dramatically increased in recent years. Although the increased interest is recent, the history of research and development in holographic storage extends back nearly 50 years, with contributions from many universities, government- and industry-sponsored consortia, and industrial companies. The uniqueness of the InPhase contribution is that they have progressed far beyond the basic research aspects of holographic storage and have persevered to address the multitude of materials, optical, mechanical and electrical engineering challenges necessary to develop a fully integrated drive-media storage system.

This book takes the reader through many details of the technical challenges encountered along this development path and of the often creative design solutions implemented to meet those challenges. Undoubtedly, the complexities of implementing a fully practical commercial system proved greater than anticipated by the InPhase team at the outset, but that is a natural occurrence when attempting to break new ground and introduce a new technology that represents so significant a departure from the incumbent approaches. To the team's credit, their approach over the years has been very open and forthcoming in describing the difficult challenges in their technical conference and journal papers. The team continues that practice in the detailed chapters of this book. Because of this openness, the book can serve as an excellent reference to developers of future holographic data storage systems and enable them to build upon and improve the technology.

From an applications perspective, the book focuses on professional archival storage, with some treatment of devices for consumer applications. Professional archival storage is a domain currently dominated by magnetic tape, and the tape technology community continues to aggressively advance its technology, following a roadmap that doubles storage capacity every 2 years. This competitive environment poses an additional challenge for InPhase, beyond the strictly technical challenges noted above.

At the same time, the demand for archival storage capacity is growing at a rapid rate, as the world continues to generate an exploding quantity of digital information. Much of this information is ‘fixed content’ and needs to be reliably retained for a decade or longer. As one measure of the enormous amount of digital information generated, a recently published study[1] reports that in 2008 Americans consumed more than 3.6 zettabytes of information (1 zettabyte $= 10^{21}$ bytes). Although the study emphasizes information ‘flow’ rather than information ‘storage’, it is clear that a significant fraction of the information described is stored in professional archival repositories.

This growing requirement for archival data retention presents an attractive opportunity for holographic data storage. The InPhase professional storage system with removable disk media is the first ever commercial holographic product to be introduced for such applications. It is indeed a pioneering development. While time will tell if the product becomes a commercial success, this book renders a wonderfully detailed and descriptive technical account of the path taken to reach this milestone.

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[1] R.E. Bohn and J.E. Short, How much information?, 2009 Report on American Consumers, Global Information Industry Center, University of California, San Diego, 2009; http://hmi.ucsd.edu/pdf/HMI_2009_ConsumerReport_Dec9_2009.pdf

Preface

This book is a result of over 15 years of research and development in holographic data storage, first at AT&T (then Lucent) Bell Laboratories and then at InPhase Technologies. The book's release is timed to roughly coincide with the release of the first ever commercial product using this technology: a professional archive storage drive using removable disk media. While major developments in holographic data storage outside of this effort are described, the focus is on explaining the design, components, and function of the technology used in InPhase's professional drive and two related consumer data storage products.

This book will enable end users of the technology to understand how the drive and media works, and how they are tested. Our hope is that other developers of holographic storage products can use this book as a basic blueprint for developing their own products using this technology.

A wide range of topics from polymer chemistry to error correction codes are covered in this book. The chapters are in large part independent, with a separate list of references at the end of each one. Although each chapter may refer to other chapters for additional detail, there is no assumption that later chapters require a detailed knowledge of earlier ones.

The first five chapters discuss the commercial market for holographic storage, and provide a broad overview of the drive and media technology. Chapters 6–8 discuss the media in greater depth. The technology underpinning the professional drive is considered in detail in Chapters 9–14. Chapter 15 covers read only memories and high speed replication of holographic media; topics that are central to the development of a consumer market for holographic storage. Finally, Chapter 16 concludes with a discussion of the future evolution of the technology and market applications.

A storage product is an amazingly complex device. As a simple example, the firmware controlling the InPhase drive is approximately 1.5 million lines of custom C++ code, which does not include almost another 1.5 million lines of other C and C++ code comprising the drive's operating systems.

The sum total of significant breakthroughs in media, material, control, optics, mechanics, data channel, and testing in the last 15 years is immense. As such, this book represents the work of over 200 people from different companies at various times.

InPhase Technologies was spun out of Bell Laboratories after 6½ years of fundamental research and development. The support of management and wonderful people at Bell Laboratories enabled the start of this long and improbable journey. We sincerely thank these companies and our collaborators, and acknowledge their many contributions to this work.

We have also had significant interaction with, and help from, Hitachi Maxell, Nichia, Alps Electric, Bayer Material Science, Sanyo, Lite-on, IBM, Datarius, and Sony.

This book is dedicated to the employees, investors, and supporters of InPhase Technologies for their amazing contributions and hard work. This book truly is a result of their labor of love. Above all, we acknowledge and thank our families for their patience, understanding, and support over all these years.

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1
Introduction

Kevin Curtis, Lisa Dhar and Liz Murphy

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.

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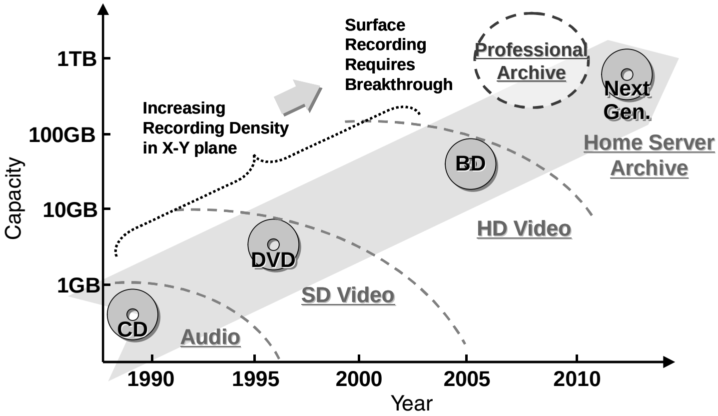

Figure 1.1 *Optical storage technology roadmap*

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,

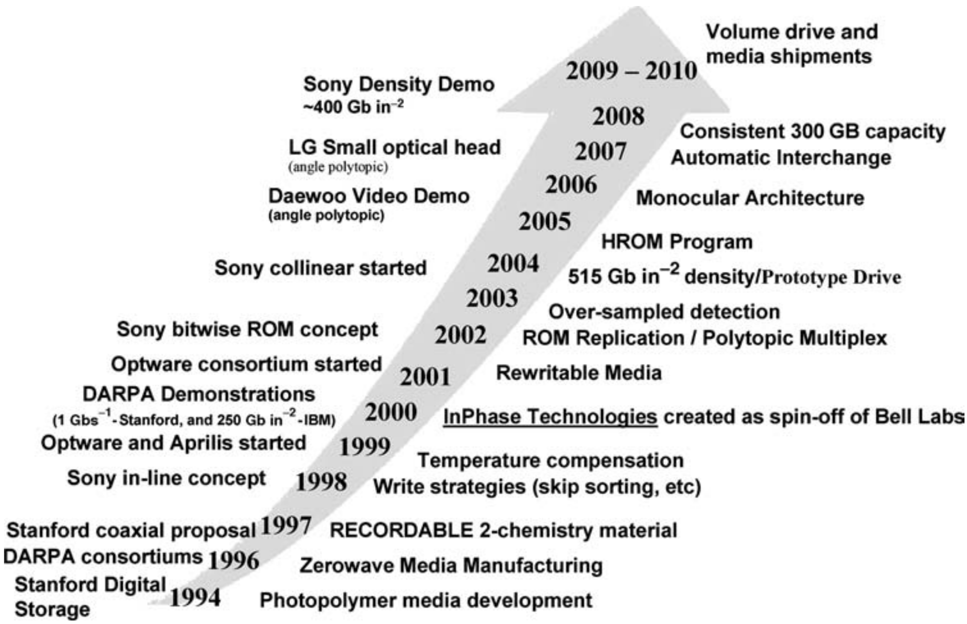

Figure 1.2 *Key holographic technology advancements of the last 15 years*

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,

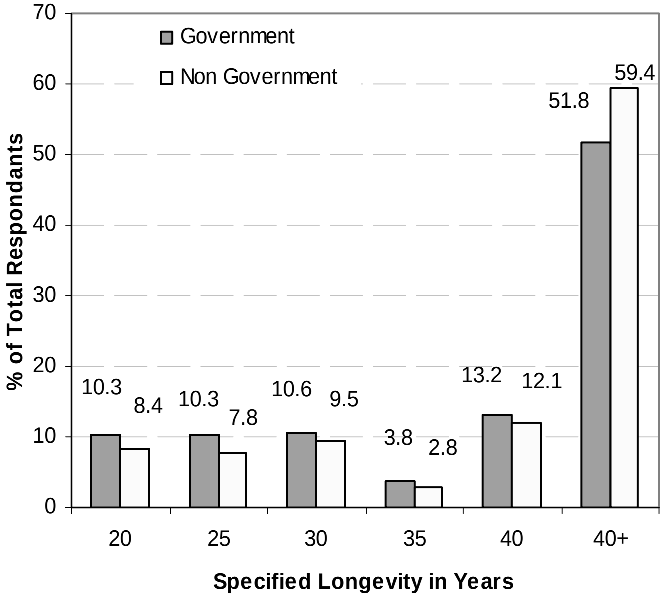

Figure 1.3 *Results of a 2005 user survey by the US Government GIPWoG group. There is a strong preference for 40+ year longevity for archival data*