Holographic Data Storage: Science Fiction or Science Fact

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ABSTRACT

To compete in the archive and backup industries, holographic data storage must be highly competitive in four critical areas: total cost of ownership (TCO), cost/TB, capacity/footprint, and transfer rate. New holographic technology advancements by Akonia Holographics have enabled the potential for ultra-high capacity holographic storage devices that are capable of world record bit densities of over 2-4Tbit/in^2, up to 200MB/s transfer rates, and media costs less than $10/TB in the next few years. Additional advantages include more than a 3x lower TCO than LTO, a 3.5x decrease in volumetric footprint, 30ms random access times, and 50 year archive life. At these bit densities, 4.5 Petabytes of uncompressed user data could be stored in a 19" rack system. A demonstration platform based on these new advances has been designed and built by Akonia to progressively demonstrate bit densities of 2Tb/in^2, 4Tb/in^2, and 8Tb/in^2 over the next year.

Keywords: holographic data storage, big data, optical data storage, holography, bit density, archive storage, cold storage, warm storage

1. INTRODUCTION

The realization of a commercial holographic data storage device has remained elusive for many decades. The most recent efforts by InPhase Technologies between 2001 and 2009 resulted in 52 functioning prototypes capable of 300GB/disk and 20MB/s transfer rates[1]. However, between the economic downturn and the fact that these capacities and transfer rates were outpaced by LTO tape, holographic data storage remained a technology that "had potential", but was never truly realized.

Akonia Holographics has created several new breakthroughs in holographic recording technology and is currently developing a holographic data storage (HDS) device that is a paradigm-shifting archive storage technology that uses lasers to record data within the volume of a polymer based media. In a single flash of light lasting a half a millisecond, up to 10 million bits of data can be stored as a page of data. In a volume less than 600um x 600um x 1500um, more than 400 such pages can be stored, giving a raw areal storage density of greater 2 Terabits/in^2.

Packaging of the polymer media can be done between two plastic substrates that are 700um thick and this will give a volumetric bit density of approximately 700GigaBytes/in^3 at a projected cost less than $10/TeraByte. This leads to an ability to permanently store (more than 50 year archive life) more than 10 Terabytes in a volume equivalent to an LTO (Linear Tape Open) cartridge (102.0 × 105.4 × 21.5 mm). This surpasses state-of-the-art HDD (168 GB/in^3, $100/TB), SSD (246GB/in^3, $900/TB) and LTO-6 tape (266 GB/in^3, $25/TB), while promising future technology advances that double capacity every 2 to 2½ years with theoretical limits of more than 37 TeraBytes/in^3.

Akonia Holographics is leveraging over $100M in R&D done at Bell Labs in the late 90's and InPhase Technologies from 2001 to 2010 and is advancing the technology to new heights. After raising funding in August of 2012, the team at Akonia has been designing a new holographic storage prototype development platform that will be the first demonstration of a new technology called *Dynamic Aperture Multiplexing*, showing scalable raw bit densities of >2 Terabits/in^2. This platform has also been designed to implement Homodyne recording as well as Phase Quadrature recording; thereby having the capability of demonstrating bit densities as high 16Tb/in^2 with very little modification to the platform. New advances in HDS made by Akonia over the past year have also shown that this new technology can attain transfer rates between 200MB/s and 300MB/s, random access times of <50ms, and 5 to 10 second latencies to as much as 4.5Petabyes (4500 Terabytes) of data within a standard 19" rack mounted library.

In the last 5 years, there have been many critical advances in industries that supply supporting technologies including: higher power 405nm laser diodes, 10 MegaPixel class camera's and SLM's, FPGA performance improvements, and holographic media. These advances combined with the state-of-the-art holographic drive architecture development by Akonia's scientists has enabled the potential for breakthrough performance in both capacity and transfer rates. It is the combination of these performance breakthroughs along with the low cost media that gives holographic storage a unique position among all the major storage technology solutions. Table 1 shows a comparison of holographic data storage with the other major technologies in the storage market. Every technology has its strengths and weaknesses and therefore serves a particular niche in the storage market. There is no such thing as "one stop shopping" when it comes to a comprehensive storage solutions; however, holographic storage has a strong competitive place in this field of technologies that have been around for 30 to 50 years and have had billions of dollars invested in their development.

	Holographic	Tape	Hard Disk	BluRay	SSD
Cost/TB Media	$10	$24	$112	$450	$900
Cost/TB System	$60	$118	$270	$485	$1,755
Total Cost of Ownership (TCO)	1x	3.2x	5.2x	13.2x	14.2x
Transfer Rate (MB/s)	200	150	150	20/200	500
Density Footprint (GB/in3)	720	177	168	155	246
Latency/Rewind Overhead	10s	100s	10ms	10s	10µs
Archive Lifetime (years)	50	20	5-7	50	10

Table 1: A comparison of critical parameters of the major data storage technologies.

2. HOLOGRAPHIC STORAGE TRANSFER RATE IMPROVEMENTS

In most data storage technologies, improving transfer rates an order of magnitude would involve many years of development, and 10's to 100's of millions of dollars in costs. A significant benefit that holographic data storage enjoys is that several critical components that are used in the technology are also found in consumer products that have been advancing significantly in the past 10 years: blue diode lasers, cameras, micro-displays, and FPGA's. Additionally, Akonia has created key breakthroughs that significantly improve the holographic media as well as increase capacities.

Unlike spinning disk type of storage technologies, write and read transfer rates in holographic storage are dictated by different processes. The writing process involves many more steps than the read process and is usually the dominant concern with respect to transfer rate in holographic storage.

The write transfer rate can be broken down into two categories: 1) Media exposure times and 2) Mechanical positioning times (see Table 2).

Table 2: Breakdown of write transfer rates into major categories

Media Exposure Times	Mechanical Positioning Times
Hologram exposure time	Galvo step and settle time
Pre-cure time per site	Media step-and-settle positioning times
Post-cure time per site	
Toast time	

Media exposure times can be improved with either better media sensitivity or an increase in laser power. Mechanical positioning times can be broken down into galvo step and settle times that dictate the movement time between holograms in an individual book and media step-and-settle positioning that dictates the time it takes to move the media from location to location. This occurs when moving from one book to another or before and after a pre-cure or post-cure event.

It is useful to delve into the details of the InPhase Tapestry drive (circa 2009) that functioned at 20MB/s to understand where improvements can be made to significantly improve write transfer rates. Table 3 shows critical drive specifications that dominate write transfer speeds. A comparison of critical parameters is shown between the InPhase Tapestry drive and the new system under development at Akonia that allows more than a 10x improvement in write transfer rates:

	InPhase Tapestry	Akonia
Average Hologram Exposure time	1.2ms	600us
Pre-cure time	12.5ms	4ms
Post-cure time	2250ms	500ms
Toast Time	1200 seconds	300 seconds
Media step-and-settle time	50ms	50ms
Galvo Step and settle time	700us	100us
Number of holograms/book	320	430
# of short stacks per book	4	3
Average Pixels per page	1.44MP	6.7MP
Objective NA	0.65	0.85

Table 3: Drive specifications that dominate write exposure times

It is also informative to look at the percent of time that is spent on the different aspects of writing holograms as shown in Table 4:

300GB/disk - 20MB/s Transfer Rate

Total Exposure time	1.6	hours	38%
Total Precure time	0.00	hours	0%
Total postcure time	0.35	hours	8%
Total Toast time	0.33	hours	8%
Total pre+post+toast:	0.68	hours	16%
Moves: pre & post cure	0.13	hours	3%
Moves: page to page	0.93	hours	22%
Moves: book to book	0.21	hours	5%
Moves: short stack	0.63	hours	15%
Total Move time:	1.90	hours	45%
Total:	**4.19**	**hours**	**100%**
Total Capacity	300	GB	
Write Transfer Rate	20	MB/s	

2TB/disk - 255MB/s Transfer Rate

Total Exposure time	1.08	hours	38%
Total Precure time	0.00	hours	0%
Total postcure time	0.08	hours	8%
Total Toast time	0.08	hours	8%
Total pre+post+toast:	0.16	hours	16%
Moves: pre & post cure	0.13	hours	3%
Moves: page to page	0.18	hours	22%
Moves: book to book	0.21	hours	5%
Moves: short stack	0.42	hours	15%
Total Move time:	0.94	hours	45%
Total:	**2.18**	**hours**	**100%**
Total Capacity	1998	GB	
Write Transfer Rate	254	MB/s	

Table 4: A comparison of write times for different component contributions between InPhase Tapestry and Akonia's new system

A summary of this table is shown as a pie chart in Figure 1. It is useful to note that the difference in the percent of component contributions to the overall write cycle going from 20MB to 255MB/s.

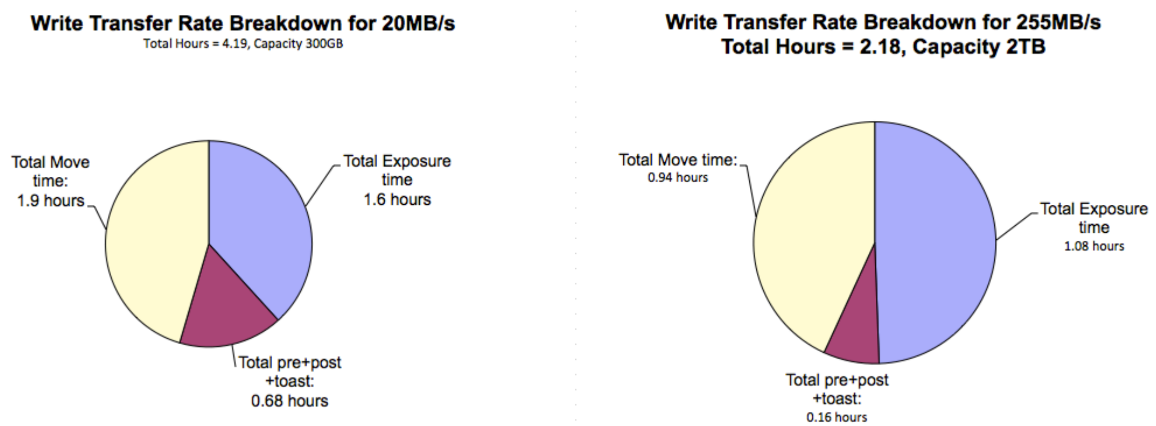

Figure 1: Write transfer rate breakdown illustrating major contributors to write transfer speeds

2.1 An Analysis of Improvements:

No improvement to mechanical disk positioning speeds (50ms) has been assumed since little new development has been done in this area. However, the galvo step and settle times can be readily improved from 700us to 100us by simply decreasing the mirror size from 18mm to 3 mm which allows significant speed improvement due to a decrease in the required torque to move and settle the galvo mirror more quickly. The decrease in mirror size can be easily accomplished with some basic modifications to the beam delivery architecture of the system. As can be seen in Table 3, galvo move times faster than 100us would certainly provide a large improvement in transfer rate since even at 100us step and settle times these moves represent 22% of the total write transfer rate time.

Read speeds are dictated by four main areas: media diffraction efficiency, movement times, laser power, and camera sensitivity. The InPhase Tapestry drive read pages at an average frame rate of 300fps (3.4ms/page). A 2x improvement in diffraction efficiency can be achieved because of improvements in media M# of Akonia's holographic media. Laser power alone can achieve a 2x to 3x improvement in required read exposure times, and with the improvement in galvo move times described above, 1 page can be read every 1.26ms (794fps) giving read transfer rates upwards of 255MB/s. The biggest improvements in both read and write transfer rates comes from the 10Mpixel Camera/SLM compared to the 1.44Mpixels used in Tapestry. However, when combined with Dynamic Aperture Multiplexing; the average data page size is 6.7MPixels instead of the entire 10MPixel format. Dynamic Aperture Multiplexing varies the page size as a function of reference beam angle (only in angle multiplexing systems) in order to take advantage of the 2x bit density improvement that is available when the Bragg selectivity is optimized with respect to the page size.

Spatial Light Modulators

The number of pixels per page is a critical parameter for transfer rate. The simplest explanation of this is that in a single exposure all of the pixels (bits) are recorded simultaneously during the exposure. If the number of pixels increases, the write transfer rate goes up proportionally given all other parameters being equal.

One might also make the mistake in thinking that pixel count impacts bit density, but this is not the case. When the lens system is optimized properly, the bit density of a single page is fundamentally dictated by the numerical aperture of the objective lens assuming a given wavelength.

Available Optical Power - Laser Power/LED Power

In the last 10 to 15 years, not only have 405nm diodes been invented, they are a very critical components of Blu-Ray players for the consumer market. This has not only driven down the cost of 405nm laser diodes considerably, but it also has driven laser powers well into the 300mW range for some Blu-Ray writing devices. This can be compared to the 60mW lasers that were used in InPhase's prototypes giving the potential for a 5x power improvement. Akonia's plan of record is to improve the laser power only by a factor of 2x. While this is moderate given the potential power with high power diodes; there is still some processing difficulty involved when high power diodes are placed in an external cavity diode laser system that must be worked out; however, in the future this would be a natural area of future process development work to access the available improvements in laser diode power.

Precure, postcure, and toasting should optimally be done with incoherent LED light at a wavelength between 370nm and 405nm. The LED revolution is well underway and much higher power blue LED's are available and have dropped in cost considerably over the last 5 years. 3 Watt LED's and greater are available from a variety of vendors. This would represent an improvement of almost 30x over previous optical power used for curing or toasting. After beam conditioning, this provides an improvement in the cure related process by at least a factor of 10.

Media Sensitivity

Holographic media is perhaps the most challenging component to improve. Fortunately, Akonia's scientists have created a breakthrough in media performance that has improved the media M# by more than 6x in laboratory tests. A media sensitivity improvement of 20% has also been realized as a side effect of the larger dynamic range. Currently, research is being done to see if there is a way to sacrifice some M# for an improvement in sensitivity. This will be the subject of future papers. In the mean time, sensitivity remains a bit more elusive to improve significantly; however, both media sensitivity and laser power dictate exposure times and cure times. The good news is that improvements in laser power can make up the lost ground in exposure times.

Move and settle times

There are two critical movement types in a holographic drive: 1) media movement, and 2) Galvo mirror movement. While there are many other components that move, these can be hidden in such a way that they don't impact transfer rates. In the analysis done in this paper, media movement has been assumed to remain the same; however, significant improvements in this area will most likely be made and this alone would vault read and write transfer rates into the 300 to 400MB/s range.

3. HOLOGRAPHIC STORAGE CAPACITY IMPROVEMENTS

Holography is attractive for digital data storage because many holograms may be written into the same volume (or overlapping volumes) of a thick recording medium, a process known as multiplexing[2]. There are many different methods of holographic multiplexing. For example, using *angle multiplexing (see Reference 2)*, one may record hundreds or thousands of different holograms in the same volume of media by using collimated (plane wave) reference beams that differ slightly from each other by their angle of incidence [3]. Each hologram may record a different object beam (or *signal beam*) that has been modulated with a different digital data pattern. During recovery, the hologram is illuminated by a probe beam. Because of the Bragg effect, only a hologram recorded with a reference beam angle at the same angle of incidence as the probe beam will produce substantial diffraction. Each signal beam may thus be reconstructed independently, allowing the digital data to be recovered without cross talk from the rest of the multiplexed holograms.

Many other techniques of holographic multiplexing are known – examples include wavelength multiplexing[4], shift multiplexing[5], and polytopic multiplexing[6]. Some multiplexing methods may be practiced in combination with others. *Dynamic aperture holographic multiplexing*, the subject of this proposal, is a new method that may be combined with other multiplexing methods. In the demonstration platform, dynamic aperture multiplexing will be practiced in combination with angle multiplexing and polytopic multiplexing.

3.1 Monocular Optical Architecture

The monocular architecture is an advanced configuration that employs a very high numerical aperture (NA) objective lens in order to maximize storage density. Both the reference and signal beam pass through this objective lens.

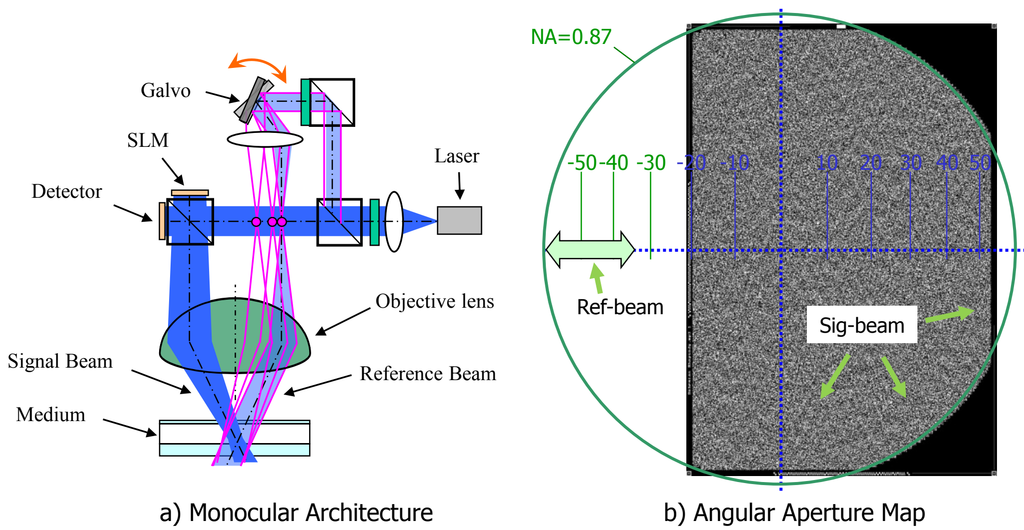

Figure 2: a) Monocular recording System. b) Monocular system angular aperture map

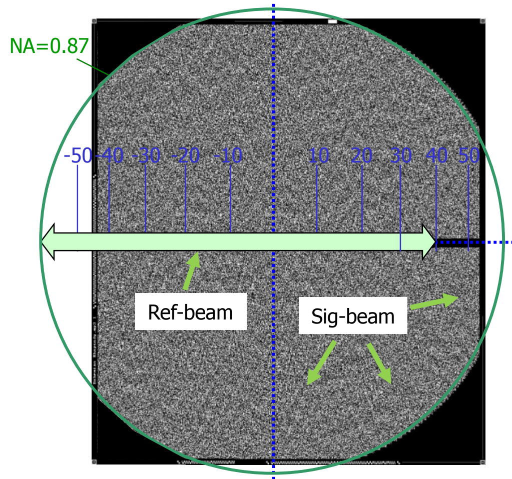

Figure 3: Dynamic aperture angle map at the maximum page size

The monocular architecture illustrated in Figure 2(a) is otherwise similar to a conventional off-axis architecture in that it is a page-oriented, angle-multiplexed, Fourier geometry. Figure 2(b) illustrates the angular aperture map of the system, wherein the *x* and *y* locations indicate the external angle of incidence of beam components into the medium. The large black rectangle indicates the location of the SLM, and the gray, pixelated region within the SLM and the acceptable NA indicates the size and shape of the data page, and thus of the signal angular aperture. (Note that in a Fourier architecture, an image of the SLM coincides with the angular aperture plane.) The arrow spanning -60^{o} to -35^{o} labeled "Ref-beam" shows the locus of the reference beams. This locus is further subdivided into, e.g., 400 finely-spaced points corresponding to the 400 reference beams used for angle multiplexing. The locus of the signal angular aperture remains constant during recording of these 400 holograms, and the signal angular aperture locus is disjoint (non-overlapping) with the reference locus.

3.2 Dynamic Aperture Multiplexing

Dynamic aperture multiplexing improves storage density by greatly increasing the scan range available for angle multiplexing [7]. This is accomplished by dynamically altering the portions of the available angular aperture used for the signal and reference beams. Figure 3 illustrates the global angular aperture map for dynamic aperture multiplexing. In the conventional monocular system of, the reference beam is confined to a scan range of 25^{o} (-60^{o} to -35^{o}), and the edge of the signal locus is separated from the reference locus by a minimum of 15^{o} (worst selectivity case) according to a Bragg selectivity design criterion. The reference locus is subdivided into, e.g., 192 reference angles, again according to a design rule based on constant minimum Bragg selectivity. According to a software model, this configuration (along with other assumptions) leads to a user capacity of 700 GB on a 120 mm disk.

In the dynamic aperture system of Figure 3(a), the reference beam scan range has been expanded to 100^{o} (-60^{o} to $+40^{o}$). The minimum separation of 15^{o} between reference and signal is achieved by dynamically changing the signal aperture according so that the closest edge of each data page is 15^{o} higher than the reference beam used to record it. Holograms may be recorded in order of ascending reference beam angle, shrinking the signal aperture as the reference beam scans from left to right in the figure.

With this geometry, the number of holograms multiplexed may be increased from 192 to 1178. Because the size of the data page shrinks as the reference angle increases, the amount of data per hologram diminishes as well. Nevertheless, the total amount of data that may be recorded increases substantially. Maximum user capacity increases from 700 GB to TB, an improvement of over 240%.

3.3 System Architecture

The architecture for the system is illustrated schematically in Figure 5b, along with the beam paths during a recording operation. One important component that is not required for a conventional system is an *aperture sharing element*, which serves to combine the reference and signal beam paths in the regions that are shared between the two.

In Figure 5, the aperture sharing function (ASE) is a component that couples the two optical systems. This can be done in multiple ways such as mirrors or PBS's. Note that the two halves of the figure are presented in two different coordinate systems with the single 'knife-edge mirror' element appearing separately in each. The knife-edge mirror is situated in the back focal plane of the objective lens where the reference beam comes to a focus. The 45^o beveled edge of the knife-edge mirror reflects the reference beam downward through the objective lens, while occluding only a narrow strip of the SLM image. This horizontal strip (shown in in Figure 5) may be easily omitted from the page data format with negligible loss of capacity. Thus, dynamic aperture multiplexing may be implemented by scanning the reference beam using the galvanometer while composing data pages of the appropriate sizes onto the SLM, and darkening the remaining pixels.

3.4 DRED Recording Medium

Because dynamic aperture multiplexing increases the number of multiplexed holograms, a recording medium with increased dynamic range will be required. Akonia has already developed such a medium and is currently testing and refining the formulation. The DRED formulation represents a major advance over the two chemistry recording medium developed by Bell Labs and InPhase.

The two chemistry medium is so-named because it consists of two separate, intermixed polymer systems. The first system, the *matrix*, is polymerized during manufacturing to form the transparent, solid recording layer. The second system consists of small species monomers and photochemicals that are able to diffuse freely through the matrix until exposed to light. This triggers polymerization of the monomer into long chains that become entangled in the matrix, creating a permanent recording of the optical field [8].

The DRED formulation (for *dynamic range enhancing dopant*) improves on the two chemistry approach by partially recombining the two chemistries. Instead of merely being entangled, the photopolymer chains are provided bonding sites to attach to the matrix covalently. In addition to dramatically increasing dynamic range, DRED technology will improve the already long archival life of holographic recordings [9].

This highlights an important feature of HDS. Traditional data storage technologies − including magnetic storage and flash memory − are fundamentally meta-stable. In contrast, inert, solid-state holographic recordings may prove able to persist long after other data has evaporated – like DNA fossilized in amber.

4. FUTURE HDS GENERATIONS

Akonia is also developing technology for future generations of HDS beyond that of this proposal. We would like to briefly describe a couple of these innovations here, lest the reader conclude that dynamic aperture multiplexing constitutes the end of the holographic data storage roadmap.

4.1 Quadrature Homodyne Detection (QHD)

Homodyne detection is the method of blending a coherent reference field with a signal and detecting the interference pattern between the two. This has the effect of amplifying the signal, eliminating nonlinear effects of coherent noise, and allowing the detection of phase as well as amplitude. Homodyne detection normally requires careful phase control of the reference field and the signal, requiring complex adaptive optics and/or phase servo loops. Akonia has instead developed a novel algorithm that allows homodyne detection to be performed simply by combining two blended signals with phase changed by 90^o. Akonia estimates this will boost S/N enough to approximately double storage density, as well as providing a host of other benefits [10].

4.2 Phase Quadrature Holographic Multiplexing (PQHM)

The ability to detect the phase of a hologram presents another opportunity to increase storage density. A second hologram can be recorded with each reference beam (e.g., two holograms at each reference beam angle for angle multiplexing), and the holograms will not cross talk provided they have a 90^o difference in phase. Thus, the technique of *phase quadrature holographic multiplexing* provides yet another doubling of storage density, and opens the door to other advanced channel techniques [11]. Together, QHD and PQHM will boost transfer rates by factors of 4 and 10 for writing and reading, respectively.

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5. CONCLUSIONS:

Akonia has developed several new breakthrough technologies that puts holographic data storage back on the path of not only being viable, but a much better archive storage solution that is very cost competitive, has critical performance advantages, archives very well, and fills a niche in being a random access technology with very low latencies to Petabytes of information. Holographic storage enjoys the strengths of tape (cheap media costs and high capacity) while not suffering from tape's weaknesses (long latencies to first data, head wear, environmentally sensitive to temperature and humidity). With Akonia's technological advances, holographic storage is not only competitive with today's technologies, but it also has the huge advantage that it is in its infancy and has decades of future potential growth and performance improvements to exploit.

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