Optical Data Storage:

The past, present, and a possible future

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Abstract:

It is my goal to introduce how optical data storage originated, and progressed to the point it is now. Further more, I will look at what improvements must be made in future technologies to facilitate a creating a competitive product for data storage. We will find that far field optics will have to be abandoned if we are to fully utilize the potential for the optical data disk.

The Beginning:

With the recent end of the so called "high definition wars", a new optical disk has taken center stage. Blu-ray technology promises super-detailed images and ultra-high capacity storage while being able to use on any platform from a television set to a computer. Yet, when you compare Blu-ray disks to other alternate forms of data storage, you find it lacking in size and data transfer speeds. An argument is made in Dror Sarid and Barry H. Schechtman's article entitled "A Roadmap for Optical Data Storage Applications", some possible alternative disk technologies are discussed. (1) Before that, the article (and I) have to introduce the history of optical disks.

Compact Disks were originally devised as an audio media, replacing vinyl records and LP's. The previous mediums used ridges on a physical medium to produce an analog signal directly correlating to the sound produced. Optical Disks started their existence in 1969 where a Philips and Sony research team came up with the idea of storing data on rings around a disk that would have pits or lands that would correspond to data. This evolved into Laservision, released in 1975. Laservision was also produced as Laser Disk (LD) and Disco Vision, and was primarily for video formats. Laservision was much more popular in Japan than the U.S.A. It quickly became a collector's item in the U.S. (9). After the failure of Laservision, the company decided to focus on audio only media. In 1982, the Compact Disk was released by Sony as an audio medium to the Japanese market. A year later the technology was introduced to the U.S. (2). Below is a comparison of CD versus LP technology popularity.

![Figure 1: Marketing comparison of early CD sales (2)](image1.png)
The CD evolved into many sub-types, the most general being the CD-ROM (generic data storage) and later the CD-RW (rewritable). In 1996 Japan released a newer technology called DVD (digital versatile disk). A year later DVD's were released to the U.S. (3) Immink's 1998 paper compares DVD's with CD technology in-depth, and even gives a 10 year projections of the future capabilities of DVD technology. The following is a table and graph used in Immink's paper to illustrate the differences between CD and DVD technology.

The important things to notice are the smaller wavelength, the higher reference Numerical Aperture, dual layer capabilities, storage size ("spot" size), and access speed. These are the things that made DVD's a viable alternative to the CD.

The Present:

The next stage of development has just begun with the introduction of Blu-Ray disk technology by Sony in 2004 (4). Schechtman and Sarid's article details the differences between CD, DVD, and Blu-Ray technologies in order to direct the field of study towards various new technologies. (1) The following is a table that Schechtman and Sarid use to...
show the differences between these three technologies, as well as HD-DVD, the main competitor of Blu-Ray in the "HD wars". The graph shows the wavelength of laser being used, the primary usage, the average access speed, and average disk capacity. In the body of their text they also give values for the spot size and NA (numerical aperture) value. For CD, DVD, and Blu-Ray respectively, the NA values are .45, .6, .85. Something not discussed here is the evolution of encoding/decoding technologies that made higher capacities viable. This was addressed in Immink's "The Story of the CD".

Figure 4: Optical Disk History

Now some may argue, with varying degrees of accuracy, that Blu-Ray has not sealed itself in the market yet, and is not "DVD's replacement". This is for the market to determine, but as a technology, Blu-Ray is a step up. Blu-Ray and HD DVD both use shorter wavelength lasers (blue lasers). But as the following graph from Schechtman and Sarid points out, Optical disks are not keeping up with Hard Disk technologies.

**X-Ray Disks?**
One option that Schectman and Sarid do not cover is decreasing the wavelength of the of the light past the blue/violet range into x-ray scale disks. There is a company called X-ROM that specializes in the development of X-ray Read Only Memory disks and the problems associated with them. The x-ray lasers use silicon doped with germanium in regions of reflection to create "bits". Some of the stated advantages include no data deterioration, Terabyte densities, and ultra-fast read out speeds. Current limitations include the ability to downsize the apparatus, and doing so in a way that is safe for consumer use. (10)

Figure 5: How x-ray readout would work
As can be seen here, Blu-Ray data size is equivalent to hard drive sizes of almost 10 years ago. The argument that is brought up in Schechtman and Sarid's article is that the physics of the disks must change in order to compete as a possible data storage medium of the future.

Comparing this to a projection in Immink's paper, "The CD Story", told through the eyes of an engineer.

It is surprising at how this forecast over 10 years ago has been very close to coming true. There was never a 20 GB DVD developed for commercial use, but Blu-Ray's introduction in 2004 introduced a 50 GB "DVD type" medium.
The Future:

When Schechtman and Sarid finished their history and comparison of current optical disk technologies, they then focus on where optical data storage must turn if it wants to stay competitive against hard drive technologies. Schechtman and Sarid do state that there are improvements to be made to Blu-Ray technology to potentially reach capacities of 200 GB/disk. This involves perfecting a six layer Blu-Ray disk, and would require much faster read/write times to be viable alternatives to hard disks.

In order to reach sizes of 500GB - 1TB, optical disks need to change their optical properties. Here Schechtman and Sarid lay out 4 different technologies that could either decrease the "spot" size, or increase the number of usable layers.

Near Field Approach:

The first approach introduced uses the evanescent near field. The spot size is limited by far field diffraction limits right now. Instead, we must change the optical physics we apply to the problem. The idea being that to decrease spot size, you must use a lens with a numerical aperture greater than 1. To do this you can use a Solid Immersion Lens or a Solid Immersion Mirror to achieve this. I find it necessary to clarify some of these concepts for my benefit, as well as the reader. The numerical aperture (NA) determines some constraints on the optical system.

The highest resolution that you can achieve with a light of a given wavelength is $\frac{\lambda}{NA}$. For laser physics the NA is $NA \approx \frac{2 \cdot \lambda_o}{\pi \cdot D}$, where $\lambda_o$ is the vacuum wavelength of the light, and D is the diameter of the beam at its narrowest spot. For all optical disks the NA determines the "pit size". Near field optics is the domain of optics relating to optics within a radius $r << \lambda$. For most applications the near field is defined as the Frenel Zone defined as $r < \frac{2 \cdot D^2}{\lambda}$. Solid Immersion Lenses (SIL's) allow a numerical aperture of higher than one through a hemispherical lens design. Tom Milster's indepth analysis of Solid Emersion Lens' and aperture systems of the near field is a great source to understand the limiting factors of the evanescent near field optics. His conclusions state the limiting factors for SIL's are; the Numerical Aperture of the SIL, and the gap between the detector and the media. Milster estimates that DVD's could increase storage density by 22x using SIL's or apertures. Milster concludes that it will be a combination of SIL’s and aperture's that will yield the most effective increase in contrast and size of "spots". Solid Immersion Mirrors provide a similar role without causing chromatic aberrations. Below is an example of how a SIL would work.
Another way to decrease the spot size of the optical disk is to use localized surface plasmon's (LSP). In theory LSP's can produce "spot" sizes close to 50 nm in size. (1) The largest set back in this technology is the limitations of the throughput. This may require parallel transducers to fix. Both LSP's and SIL's have the problem of dealing with the near field, where the space between the disk and detector/lens is on the order of 10-25 nm. At this size, dust and scratches can cause serious detection problems.

Another approach is to use Super-RENS (resolution near-field structures). These structures do not need the close proximity, and are designed by integrating a metal or metal-oxide nanostructure into the disk material. Spots in the range of 37 nm are able to be read with an error in the order of 10^-3. Schechtman and Sarid describe the process as, "High fields excited locally around each structure generate high temperature spots in which the composition of the nanostructure is modified, resulting in a change of the effective refractive index." (1) This is still in the development stage, and needs more research before a commercial product can be achieved.

**Volumetric Techniques:**

The second method of increasing bit density is to increase the number of layers used in a single disk, hence named the volumetric method. There are two specific ways Schectman and Sarid analyze to accomplish this task. The graph below from Schectman and Sarid demonstrates the data densities of various volumetric techniques.
Figure 9: Transfer rates and Data capacity of various volumetric approaches

The first is called the bit-wise approach. This system is being developed by Call-Recall and Landauer. This technology defines "soft" layers, that are written at a prescribed depth using a two-photon absorption method, and read back using the fluorescent property of that layer. Parallel read back would increase data transfer rates. Researchers working on this technology suggest layers in the order of 100, while practicality limits the number of layers to several tens, according to Schechtman and Sarid. (1)

The second is the use of holographic disks. This technology is on the verge of being commercially available, and is being pursued by InPhase, Optware, and Sony. There are two major ways to read/write from a holographic disk. The first is to use angle multiplexing, and the second is using the collinear phase-conjugation. InPhase has produced polytopic multiplexing disks that have reached 300 GB, with a projection of using multilayered holograms to create a 1.6 TB disk. Optware is producing collinear multiplexed disks, and project a expected 2 TB disk, while claiming backwards
compatibility with DVD technology. Sony and other researchers are working out a micro-reflector hologram technology that boasts 20 layers per disk, with a total of 500GB per disk. (1) One of the biggest obstacles holographic disks had to overcome was the mechanical vibrations introduced into the system. To deal with this, some formats proposed include a cassette type version that holds the disk. Here is a demonstration on how the collinear holographic approach would work.

![Collinear™ vs. Two-Axis Holography](image)

Illustration 10 shows that compared to the more complex two-axis approach, the Collinear method is compatible with CD and DVD technology for backwards compatibility, and utilizes one objective lens rather than 6 lenses in the two axis method. Doing away with the two-axis method, the holographic disk method becomes very practical, and viable as a new optical disk technology.

![HVD Disc Structure](image)

In figure 11 we see the holographic disk utilizes two different colors of lasers to read and write data. There is a green or blue laser used to record data, and a red laser to reference
the location on the disk. These reflective pits in conjunction with the red laser are the key to creating a rugged system, and deals with previous vibration problems. Manufacturer's of holographic disks propose an increase in the holographic data density, as can be seen in figure 12.

![Figure 12: Projected future of HVD](image)

As can be seen from the illustration above, HVD-R technology is encased in a cassette type covering offering larger data densities.(11)

**Conclusion:**

Optical disks have gone through 3 generations of changes, and have a sound projection into the future. That said, in order to stay competitive with other data storage devices, optical disks must increase in data density significantly. For commercial applications they must increase their product lifetime and data transfer rates as well. They can accomplish this by either decreasing the "spot" size, or increasing the number of layers within a given disk. Either way, we must delve into a new level of physics to solve this issue.
References:


