# Development of Holographic $SiO_2$ Memory for Ultra-Stable, High Density Data Storage

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**Introduction**

High capacity memory is an imperative today. In the past decade, advancements in CMOS technology have granted massive computation power to society, further accelerating scientific pursuit and bringing unrivaled convenience to everyday life. However, as a result, data generation rapidly outpaces current storage systems. IBM estimates that of the ~35 zettabytes of data generated annually, only 0.5% is "hot", or used at any given time [1]. A pressing question is what to do with the other 95.5% of cold data. Current archives are scattered, relatively unorganized and power intensive. These are problems that will only get worse with time, but erasure could potentially destroy important information or history. A new media for mass storage designed specifically for cloud usage would greatly alleviate the burden of mass cold data, as well as significantly simplify the current system. Particularly, all-optical hologram storage offers exciting potential for ultra-stable, high density memory that is suitable for modern needs.

**Holographic Memory**

Optical memory devices can be placed into 2 categories, opto-electric or all-optic. The former uses light to assess or manipulate carrier mobility [2], analogous to reading and writing with CMOS memory. This is active and suitable for computing memory. The second, all-optic memory, offers different advantages. Categorically, all-optic memory is not reprogrammable and instead relies on the high internal stability of its storage medium. Data is encoded directly into the medium's structure, creating a non-volatile memory with no power consumption. This sort of storage has already enjoyed wide usage today in the form of write once read many (WORM) memory devices like CD-ROMS and other disc storage.

WORM memory has largely fallen out of favor in the past decade due to computing needs and the explosive development of CMOS technology. However, research has still gone into different data encoding schemes to make it more suitable for modern day data generation. One of the largest advancements has been in writing and reading technology. Disc storage was largely constrained to the surface area of the disc, but now memory can be stored and read volumetrically into a unit called a *voxel*. This is called holographic memory (a collection of voxels), and when combined with modern day manufacturing precision, makes an incredibly high capacity, high stability, low power option. Holographic memory is the perfect solution to the problem of cold data problem.

**Encoding Data**

A hologram's memory capacity is directly proportional to the size of its voxel. Major considerations determining voxel size include 3 interdependent factors: how small the voxel can be made, how precisely a voxel can be placed relative to another, and how reproducible these voxels are. Aside from precise fabrication and machining, the media is extremely important as it the data itself, as every voxel. The medium should lend itself to interesting features, as this determines the information density of the voxel. Every feature per voxel is a dimension by which to encode the data. Phase change materials (PCMs) immediately come to mind as a candidate material due to its manipulability yet long endurance.

The ubiquitous $Ge_2Sb_2Te_5$ (GST) is an excellent media candidate for high density holographic memory. PCMs such as $Ge_2Sb_2Te_5$ have been typically explored for use in resistive random-access memory due to their ability to achieve multilevel, stable memory repeatably with good endurance and scalability. Induced domain change affects the materials resistivity and even more so its optical properties. A recent demonstration has proven that it is possible to achieve extremely precise optical control of GST cells (Li et al., 2019) [4]. The authors displayed a novel variable double laser pulse that ensured any one of 34 desired states could be achieved with a single execution. This amount of states corresponds to 5 bits of binary data per cell, offering an extremely efficient and quick optical memory cell. However, the device is ultimately limited by its size and complexity. A programmable optical GST PCM device would require a photonic waveguide for every cell, complicating fabrication and increasing voxel size. A multi-level scaled cell could be used as holographic WORM memory but programming each cell individually would be detrimentally time-consuming for any significant amount of data. Though GST exhibits optimal optical properties, it may not be suitable for holographic memory. Fortunately, there is a method for encoding data that does not require individualized input channels.

In the early 2000's, it was discovered that highly irradiated $SiO_2$ glass would develop ordered defects. These defects took the form of nano-gratings, or equi-spaced slots, perpendicular to the polarization direction of radiation (figure 1). A recent study from the University of Southampton has finally proposed the mechanism (Beresna et al., 2012). In the work, researchers developed a method for achieving these nano-grated structures in $SiO_2$ glass in a controllable manner [5]. With precise control, a high power, femtosecond laser pulse can be used to briefly induce excitons and polaritons at the focal point. These particles rapidly recombine, which tears apart Si and $O_2$ bonds and causes a sudden expansion of the $O_2$ gas before diffusing back into surrounding material. The results are permanent nanopore structures embedded into the $SiO_2$ that are birefractive (polarization and direction dependent refractivity). For the purpose of holographic memory, this presents a unique opportunity. Birefractivity gives these features 5 degrees of freedom: slow axis orientation (polarization), strength of retardance (intensity), and 3 spatial coordinates. The result is an outstanding nanosized, 5-bit voxel. The encoding process can be easily controlled to create and arrange these voxels in precise locations. Adjusting the laser to create different layers maximizes the density of a potential device. This natural phenomenon makes $SiO_2$ an ideal material for dense information encoding.

**5-Dimensional Glass Storage**

Researchers at the University of Southampton have developed this discovery into usable memory [6]. A Yb:KWG laser operating at 300 nm was used to fired 6.3µJ pulses at 200 kHz with tunable duration (270-800 fs) onto $SiO_2$ glass. Each voxel was comprised of a nanograting made from a pulse. The X and Y directions were controlled by moving the substrate, while the Z direction was controlled adjusting focal point of the laser. 3 layers were inscribed in the interior of the sample using this method.

The nanogratings appear as dots, and groups of 1-100 could be generated at a single time. The instrument used could generate multiple light intensities, so strength of retardance was used to multiplex

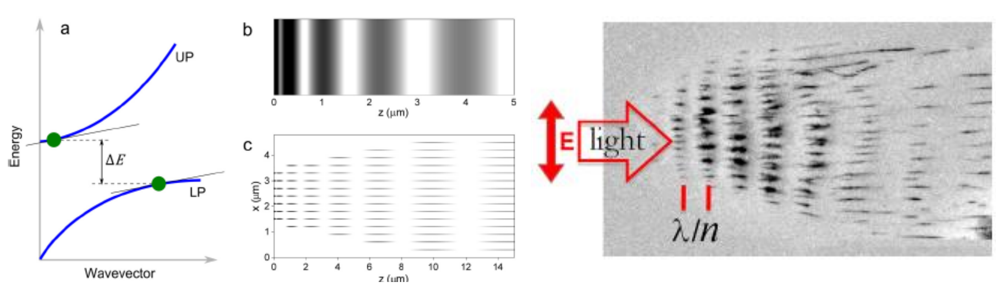


**Figure 1**: (left) theoretical simulation of formation of nanograting. (right) SEM image of self-assembled nanograting. **Images from Beresna et al. 2012 [5].**

the signal, increasing write and read speed. Light polarization caused some challenge, as the write speed would be severely bottlenecked by any mechanically rotating polarizer (10ms). Therefore, a motion free polarizer was achieved by using a half-wave plate matrix to split the beam into 4 more constituent polarizations in addition to the cardinal states for a total of 8 polarization states. Continuing in this manner, a disc ($119.4mm_{\phi}$ and $1.2mm_{z}$) with 360 TB capacity was recorded, with 3.7μm XY spacing and 20μm Z spacing between voxels. This corresponds to a practical storage density of 439 $TB/in.^3$ This is 2500x the density of current optical disc storage, with room for improvement.

**Reconstruction**

The "read many" portion of WORM memory is equally as important as the "write once" half. The context of this problem is mainly optimization. Though the form of the encoded data is known, the actual decoding process is lengthy due to the density of information and signal processing required. The input must be circularly polarized to allow all possible polarization states, and then bandpass filtered to concentrate the signal. After this is passed through the layer containing information, the resulting signal is collected and amplified by a birefringence measurement system, which utilizes a liquid crystal analyzer to characterize the state of polarization. The intensity shift is calculated to provide the fifth dimension, and once multiple layers have been decoded, the resulting voxels can be reconstructed back into usable bit form (Figure 2). In the same Southampton study, 11664 bits were encoded onto the glass and readout. The reconstruction resulted in 42 bit errors (0.36%). This was further lowered to 0.22% after further calibration.

Accuracy is negatively impacted by layer count, as deeper layers will naturally have incrementally higher amounts of interference regardless of high sharply focused the light is. In a sister project by Microsoft, Project Silica (Anderson et al., 2018) recreated the discs with an additional 7 layers (10 total) and even tighter voxel spacing. Readout accuracy averaged 75.8% across the 10 layers, with a decrease of 10% while reading the layers 9 and 10 [7]. However, because only multidigit bits are required for final reconstruction, the raw output data can be corrected before calculation. Researchers passed intensity and polarization data through a deep learning based neural network to filter out anomalous values due to scattering. This greatly improved accuracy to an average of 99.47%, with 100% accuracy in the first 9 layers. More importantly, it creates another direction to improve the technology, as the output can be optimized by methodology or data interpretation.

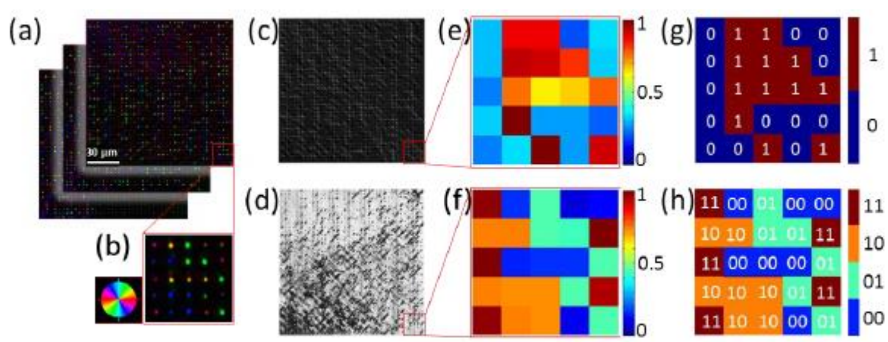


**Figure 2**: 5D optical storage: (a) birefringence measurement of the data record in three separate layers. (b) Enlarged 5x5 dots array. Pseudo color indicated the orientation of slow axis. (c) Retardence distribution retrieved from the top data layer. (d) Slow axis distribution retrieved form the top data layer. Enlarged normalized (e) retardance and (f) slow axis matrices with its corresponding (g), ()f retrieved binary data. **Images and caption from Zhang et al. 2019 [6]**

**Stability and Nonvolatility**

Optical device lifetime is solely dependent on the optical medium. For the memory disc created by University of Southampton, this material is fused silica glass ($SiO_2$). Fused silica, like many other glasses, is extraordinarily stable. Its melting point is in the range of 1500ºC, well beyond any electronic or storage material used today. Additionally, silica is chemically resistant against acids¸ oxidation, UV exposure, and scratching. With proper care, glass is impervious to time.

2 Characterization tests were conducted on the devices to observe the voxel decay, high temperature and room temperature storage (Zhang et al. 2014) [8]. In the former, devices could last annealing at 1000ºC for 2 hours before the memory was compromised. The room temperature decay time was calculated by measuring the effects of writing at different temperatures. This differential could be used to calculate how much activation energy was required to collapse the nanopore given pore dimensions and material properties. Fitting corresponding activation energies to the Arrhenius model, a linear fit estimated an astonishing room temperature lifetime of $3*10^{20}$ years, +/- 1 magnitude. While the model does not account for temperature variations, such extrapolations are not wholly baseless. If kept under the proper conditions, glass memory could be a permanent mass storage option.

**Improvements**

Despite such characteristics, glass memory storage has significant room for improvement. The information density can be increased as resolution for writing, reading, and polarization states, as well as number of layers or voxels per device. However, speed is the largest weakness.

Because all signal processing and demultiplexing takes place off-device, the process is heavily bottlenecked at the reading and writing processes. Though birefringence measurement equipment is well studied and tuned, extremely large data sets, especially terabytes of data, still prove cumbersome for any serial procedure. Current laser pulse processes can only run at 500kHz [4]. Factoring in mechanical stage movement, 1 dot, containing 5 bits, takes 5-10μs to write. Therefore, 1GB would take 3 hours to write. Reading is significantly faster, as multiple voxels can be read at once in image form, but the speeds are still hardly usable. The solution would be to somehow parallelize the reading and writing procedures, which would bring down these times linearly. A number of studies have investigated bringing demultiplexing processes on board to spread the load. These include integrated photonic waveguides and resonant cavities that could split and guide output signals to multiple instruments and remove the need for retardance calculations [9, 10, 11,12]. However, new writing solutions have yet to been.

Energy is another consideration. As nonvolatile WORM memory, there is no passive energy required to refresh data, but the writing phase is power intensive, requiring ~2kWh to record 1 gigabit of data. Economically this comes to approximately $1.60/GB solely for writing energy ($50 trillion for 34ZB), and much more considering operation associated fees. Despite the high number, the US Energy Technologies Area repot that approximately 80 billion kWh are consumed by US-based data centers [13] annually and rising. Critical cold data could be moved to glass storage, overall saving billions of kWhs.

**Conclusion**

A 5D all optical storage was discussed that utilized an $SiO_2$ glass substrate. The device presents unprecedented storage density (>439TB/in.$^3$) and memory endurance (~$3x10^{21}$ years). With such incredible characteristics, it provides a permanent solution to the problem of cold data and serves as a vital piece in restructuring global data infrastructures. In a major advancement in memory, glass memory offers the unique opportunity of forming an eternal archive.

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