Optical Mass Storage and Retrieval at Rome Laboratory

Joshua L. Kann, Brady W. Canfield, Capt, USAF, Albert A. Jamberdino, Bernard J. Clarke, Ed Daniszewski, and Gary Sunada, Lt, USAF

Rome Laboratory/IRAP
32 Hangar Rd.
Rome, NY 13441-4114
(315) 330-4581
kannj@rl.af.mil

ABSTRACT

As the speed and power of modern digital computers continues to advance, the requirements on secondary mass storage systems grows. In many cases, the limitations of existing mass storage reduces the overall effectiveness of the computing system. Image storage and retrieval is one important area where improved storage technologies are required. Three dimensional optical memories offer the advantage of large data densities (on the order of 1 Tb/cm^3) and faster transfer rates due to the parallel nature of optical recording. Such a system allows for the storage of multiple gigabit sized images, which can be recorded and accessed at reasonable rates. Rome Laboratory is currently investigating several techniques to perform three-dimensional optical storage including holographic recording, two-photon recording, persistent spectral hole burning, multi-wavelength DNA recording and the use of bacteriorhodopsin as a recording material. In this paper, the current status of each of these on-going efforts is discussed. In particular, the potential payoffs as well as possible limitations are addressed.

1.0 Introduction

Air Force Command, Control, Communications, Computing, and Intelligence (C4I) systems must effectively store, retrieve, and manage massive amounts of digital data. Optoelectronic and massively parallel computing demands multiterabit memories and near real-time write and retrieval rates. Current Air Force systems range from centralized terabyte and petabyte storage comprised of large objects (images) to distributed heterogeneous databases that contain many small and large objects (open source databases). Although technologies for storage, processing, and transmission are rapidly advancing to support centralized and distributed database applications, more research is needed to handle massive databases efficiently and achieve the Air Force goal of "Information Dominance".

The goal of our research is the retention of data for potential future analysis in a cost-effective manner. The more relevant data remains on-line for approximately five years,

organized with the most critical data accessible in the least amount of time. It is expected that 2 to 5 TB of new data will be processed each day. The total size of the database (both on-line and off-line) could be as large as 20 PB with about 300 TB of data stored on-line. Access time is about 5 seconds for the data less than a week old, about 30 seconds for data under two months old, and on the order of minutes for the data up to 10 years old. To meet these demanding requirements, we are currently investigating various approaches to ultra dense, highly parallel three-dimensional optical memory storage systems. This article traces the recent history of optical data storage and updates the status of our research efforts in this field.

In the mid-1970s and early 1980s optical storage reached the consumer market. Industry giants like RCA and Philips developed and marketed playback devices and large format laser disk systems for home movie viewing. While laser disks never generated a large, broad-stream consumer market (VCR is still the dominant technology for home movie viewing), compact disk (CD) technology quickly became the primary method for distributing and listening to high-fidelity music. The introduction of laser diode devices made compact disk systems a viable consumer product. Laser diodes operating within the near-IR (infrared) spectrum allowed 1μm embossed pits to be easily detected. The new laser technology, in combination with powerful error detecting and correcting codes, enabled SONY and Philips to introduce the first CD audio product a decade ago.

Better optical media, more powerful laser diodes, and very precise, low-mass optics have propelled the growth of optical disk systems[1-3]. The next-generation device introduced in the mid-1980s provided a flexible Write-Once, Read-Many (WORM) capability. This enabled end-users to record and playback computer data from the same drive. Rome Laboratory continues to sponsor work in this area to further exploit the benefits of new storage technology. An early Rome Laboratory prototype used an argon laser to record and playback digital data from a 12.5-inch plastic-based optical disk. Further investment led to the delivery in 1982 of a large-capacity optical jukebox for satellite imagery storage and retrieval applications. The jukebox held 100 WORM disks that provide a storage capacity of one terabyte.

The third generation of optical disks, today's rewritable systems, offer record, playback, and erase capabilities. These Magneto-Optical (MO) disks are composed of a rare-earth alloy and transition materials, which often include terbium, iron, and cobalt elements. Rewritable optical disk storage is playing a larger role in mass data storage for many military applications; particularly, those applications that require reliable operation under harsh operational environments. Commercially, MO disk drives continue to make an impact on the mass-storage market.
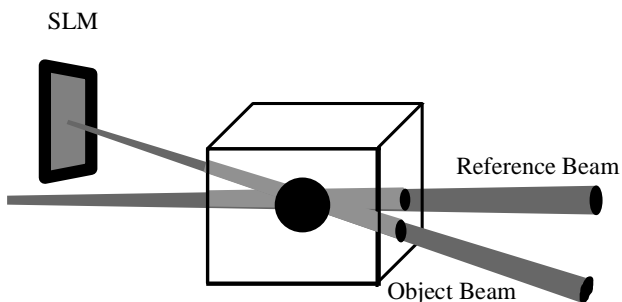
While the storage technologies discussed above store serial information in a two-dimensional plane, three-dimensional (3-D) memory devices store two-dimensional information (bit planes) throughout a volume. In this paper, we discuss the current status of our ongoing efforts in several areas of 3-D optical memory. Section 2 investigates a

variety of 3-D memory storage techniques. Holographic and two-photon storage methods are discussed in detail. Both system and material aspects are addressed. In addition, three other techniques: Persistent Spectral Hole Burning (PSHB), the use of bacteriorhodopsin (BR) as a storage medium and recording in DNA molecules are also discussed. Finally, in Section 3 a summary and some conclusions are provided.

2.0 Various three-dimensional recording techniques

By definition, a 3-D memory is a single memory unit where three independent coordinates specify the location of stored information. By storing information in volumetric media, we can achieve very high densities ($\sim$1Tb/cm^3). These 3-D memories are generally classified as bit-plane-oriented and holographic. In *bit-oriented 3-D memories* each bit occupies a specific location in a three-dimensional space. This differs significantly from *3-D holographic memories*, where the information associated with each bit is distributed throughout the memory space. Bit-oriented 3-D memories generally use amplitude recording media, while holographic memories use phase recording media. In bit-oriented 3-D memories, the coordinates that specify the location of information can be spatial, spectral, or temporal, giving rise to a variety of 3-D memory concepts that use different materials with various properties. For example, materials that exhibit two-photon absorption are the basis for true volume memories, while materials utilizing spectral hole burning provide a storage medium for spectral/spatial storage. In addition, materials that exhibit the photon-echo effect could, in principle, lead to temporal/spectral/spatial storage.

In 3-D memories, read, write and erase operations are performed on the entire bit plane, giving rise to a tremendous memory bandwidth increase over conventional 2-D bit-oriented memories. Through the inherently parallel nature of data manipulation, high-speed reading and writing of an entire memory plane becomes feasible. These considerations make 3-D memories very compatible with emerging, highly integrated parallel array processors and optoelectronic multiprocessors.

2.1 Holographic data storage

Holograms for artistic posters and pictures started gaining popularity in recent years due to the maturation of several key technologies. These same technologies provide a potential to store data with smaller system sizes but larger data capacity and faster throughput rates[4-6]. While this idea is not new to the data storage world, it was only recently considered practical due to the emergence of improved critical
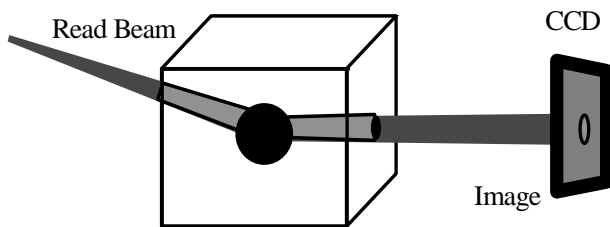
Figure 1. System used to record holographic data. A reference beam and object beam are interfered within the recording medium. The resulting interference pattern is recorded within the medium.

components such as improved laser diodes (LD), Spatial Light Modulators (SLM), and Charge-Coupled Device (CCD) detector arrays. Holographic memories are capable of large data densities ($1Tb/cm^3$) and are capable of processing data in parallel, affording fast data transfer rates, high storage density, and small physical size.
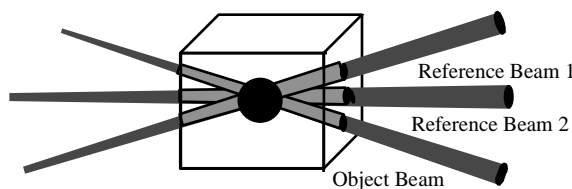
A hologram is essentially a recording of the amplitude and phase of a wavefront. This is in contrast to conventional photography, where only the amplitude of the wave is recorded. A hologram is recorded, or written, by the interference of two beams, an object (signal) beam and a reference beam, as shown in Fig. 1. Readback is accomplished by illuminating the hologram with the <u>nearly identical</u> reference beam used in recording. The diffracted beam is then a reconstruction of the object beam's wavefront (amplitude and phase) as shown in Fig. 2. To create the extremely high data capacity, data pages are stored in the same physical space of the media, but are written and read by multiplexing. Multiplexing is a way of giving a data page a unique address. Typical multiplexing methods used for holographic storage are angular, spatial, and phase multiplexing.

Figure 2 System used to read previously recorded holographic data. The reference beam playback the recorded data. The data is then imaged onto a CCD.

Angular multiplexed holograms, shown in Fig. 3, change the angle of incidence of the reference beam on the storage medium without changing the location of the area, or spot, being recorded. Individual holograms are recorded in the same spatial location, but with varying angle of incidence off the reference beam. Figure 4 shows how angular multiplexing changes the reference beam angle without changing the recording location. The figure shows three collimated beams with different angles of incidence illuminating the storage medium. All three beams intersect at a common location where the hologram is located. An important consideration for angular multiplexing systems is the need for sophisticated, non-mechanical beam steering devices, to allow for acceptable page-access times.

Figure 3 Basic premise of angle multiplexing. Multiple holograms stored in the same spot, all recorded with a reference beam at a different angle.

Phase multiplexing uses reference beams with different phase fronts to write composite holograms associated with the object beam. Each reference beam consists of a

set of plane waves with a unique phase distribution. This phase distribution represents the address of the recorded information.
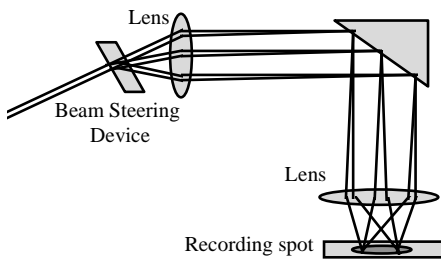
Figure 4 A system used to perform angular multiplexing. A beam steering device is used to modulate the angle of incidence of the reference beam.

Holographic memories using phase multiplexing have the same data storage capacity as angle multiplexing, but involve different problems generating the phase codes. We are working with Surface Optics Corporation, in San Diego, California, to develop a compact 3-D storage system using this method, which will store 26 GB and have a footprint of one square foot for the entire system.

Finally, *Spatial multiplexing* is a method used to change the recording spot location to a different location in the medium. In volume holography, holograms recorded on top of each other will ultimately reach saturation of the recording medium unless redirected to a different spot. Spatial multiplexing can be combined with angle or phase multiplexing to increase the storage capacity of the memory device. Holograms are first stored in one spot up to their practical limit using angular or phase multiplexing, then the information beam is redirected to a different spot using spatial multiplexing to fill the next area with a new page of information.

Optimizing the number of holograms per spot is a key to finding the best system. The most successful efforts apply angle and spatial multiplexing. Researchers with the Psaltis Group at the California Institute of Technology have demonstrated the storage of 160,000 individual holograms in a 2 cm x 2 cm x 4 cm crystal of $LiNbO_3$. The photorefractive $LiNbO_3$ crystal is thick, and can have a high number of holograms per spot. The thickness determines the number of holograms that can be multiplexed in a given area of material before reaching the point where saturation occurs and the data resolution decreases. As more holograms are recorded the diffraction efficiency of each (related to the signal strength during readback) decreases. Thus, a trade-off exists between signal strength and data capacity. While, thin holograms cannot store as much data as thick holograms, they do require simpler, lower cost optical systems and are cheaper to fabricate. We are funding two efforts with Holoplex, Inc. in Pasadena, California to make data storage systems out of thin film photopolymer disks. Each of these disks will store 2.8 Tb, with 17 ms access time, and each disk can be recorded in 60 sec.

2.2 Two-Photon Storage In addition to our holographic work, we are also investigating 3-D memory storage system which utilizes two-photon absorption[7-8]. We are working with Call/Recall, in San Diego, California, to develop a two-photon based optical memory. As with holographic systems, these systems are capable of data densities up to $1Tb/cm^3$. This system also takes advantage of the parallel nature of optical recording, allowing for a page of digital data to be written (or read) simultaneously. We have invested in this technology for the past five years and have recently developed a

demonstration Read Only Memory (ROM) system. It is hoped to have functional WORM and read/write/erase systems within the next few years. Currently, a great deal of research is being done both in the system and material areas of this technology.

The basic premise of a two photon recording system is the simultaneous absorption of two photons whose combined energy is equal to the energy difference between the initial and final states of the recording material. This simultaneous absorption results in a change in the molecular structure of the material. This structural change alters various properties of the material, including index of refraction, absorption spectrum and fluorescence spectrum. Therefore, by intersecting two optical beams, spatially and temporally, the material's optical properties can be altered locally and are addressable anywhere within a three-dimensional space. Digital data is written in this fashion, with the ultimate limitation on storage capacity set by diffraction effects in the optical system. Data readout is accomplished by probing the material with a single read beam to measure a change in one of the material's optical properties.

The current ROM system architecture uses picosecond pulses of the first and second harmonic ($\lambda_1 = 1064$ nm, $\lambda_2 = 532$ nm) of a Nd:YAG laser. A schematic of the optical system is shown in Fig. 5. Image storage (recording) is shown in Fig. 5(a), while image retrieval (readout) is shown in Fig. 5(b). Digital information is recorded in the two-photon material as pages of digital data, the data planes separated in the axial direction. (Currently, the material is fabricated in a cubic shape, but we are investigating other
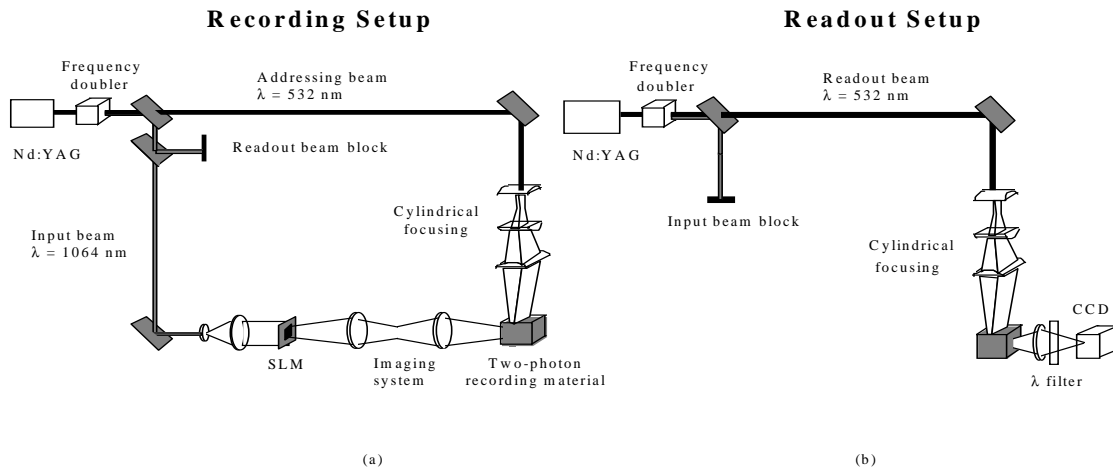

Figure 5 The recording (a) and readout (b) systems used for a two-photon memory.

geometries.) The input (data) arm of the system ($\lambda = 1064$ nm) is spatially modulated

with a SLM and imaged to the proper plane within the cube. A second, addressing beam (λ = 532 nm), propagating orthogonal to the input beam, is cylindrically focused throughout the cube. A page of data is recorded when the input beam and addressing beam simultaneously illuminate the image plane. The axial resolution is limited by the divergence of the addressing beam, while the lateral resolution is determined by diffraction effects and aberrations in the input arm. A more detailed discussion of data parallelism versus density is given later in this section. Readout is accomplished by measuring the fluorescence of the material. The input beam is blocked and the 532 nm beam is cylindrically focused to read the proper data page. For the unwritten material, the 532 nm beam is unabsorbed and passes through the system. However, for the written form of the material, the readout beam is absorbed, exciting a fluorescence at a longer wavelength. The readout plane is then imaged through a wavelength selective filter onto a CCD. Thresholding of the individual pixels of the CCD is performed to digitize the data.

A variety of recording materials have been proposed. The proper material must posses several key characteristics in order to be considered. These characteristics include: photocromisim (the change of chemical structure after excitation by light), a fluorescence in one of the two chemical states, stability of both states at room temperature, ability to read data 10^6 times without loss of information, high quantum efficiency of the read form fluorescence, and a wide enough wavelength shift between the read beam and peak of the fluorescence spectrum to prevent cross-talk. In this paper, we discuss one of the more
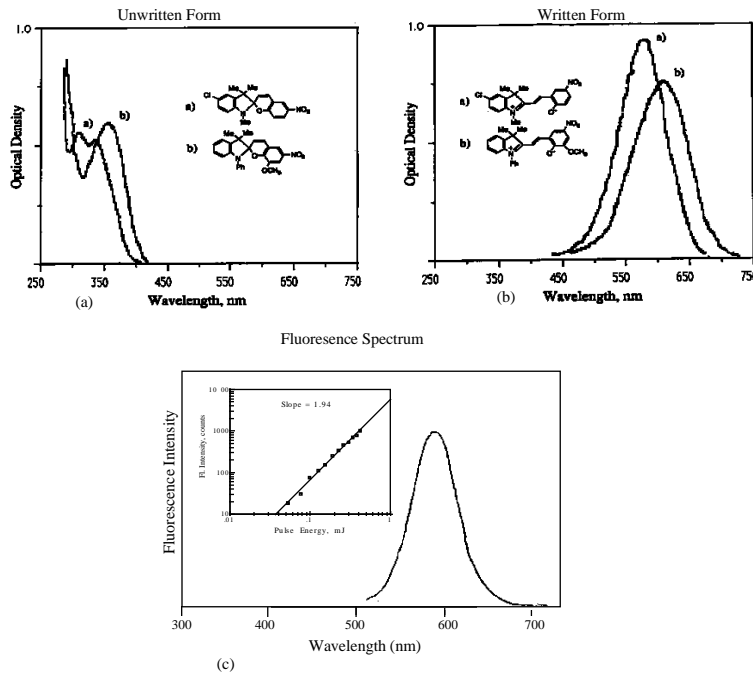
Figure 6 The absorption (a-b) and fluorescence (c) spectrum for two different types of SP compositions.

promising candidates, Spirobenzopyran (SP).

Spriobenzopyrans molecules are composed of two distinct molecular components linked by a sp^3 hybridized carbon. Simultaneous absorption of a 532 nm photon and a 1064 nm photon alters the chemical state of the material, as shown by the absorption spectra in Figs. 6(a) and 6(b). The unwritten form, Fig. 6(a), is colorless in appearance and shows strong absorption in the ultraviolet ($\lambda < 400$ nm) portion of the spectrum. However, the written form, Fig. 6(b), is colored in appearance and shows strong absorption in the 550 nm spectral region. The fluorescence spectra of SP, shown in Fig 6(c), is peaked around 600 nm. Note that the this peak is sufficiently separated from the read wavelength to prevent cross-talk during readout. Figures 6(a) and 6(b) show two species of SP. To fabricate solid, stable recording materials, the SP is dispersed in polymers such as PMMA. This alters the absorption and fluorescence spectrums slightly, but does not effect the basic system premise discussed in the previous paragraphs.

Currently, a working ROM system has been built and is used for writing and readout of pages of digital data. The system uses a 1 cm^3 cube of SP as a recording material. The system has been used to record 100 planes of data with a separation of 27 μm between planes. The input beam is spatially modulated with the use of chrome masks. The mask's resolution is 100 x 100 μm^2. Dynamic focusing is performed by moving the cube. Currently no dynamic aberration correction is performed. With a demagnification in the system of 13.5, the recorded bits are 7.4 x 7.4 x 27 μm^3 resulting in a density of 676 Mb/cm^3. Data readout is accomplished with the use of a HeNe laser ($\lambda = 543.5$ nm), and a 640 X 480 CCD array. While the system's density is well below our desired goal of 1 Tb/cm^3, the system allows us to demonstrate and improve on the current technology.

Using this system initial Bit Error Rate (BER) characterization is being performed. In order to be competitive with existing mass storage systems, raw BER's on the order of 10^{-6} must be obtained. Several analog equalization techniques and digital error-correction and detection algorithms are being studied. In addition, we have begun work with the University of Pittsburgh on an optoelectronic cache memory system which will act as cache memory between the optical memory, and a single or multiprocessor computing environment. By caching a page of data during a memory read, the relatively slow access time of the system will be significantly lowered, since the access time of the cache memory is orders of magnitude faster than that of the two-photon memory.

There are several obstacles to overcome in this rapidly developing technology. The first involves cube fabrication. Important characteristics are surface quality and material homogeneity. Surface quality is especially important, since defects in the material's surface will result in scattering of the light beam and optical aberrations of the transmitted beam. Using injection molding techniques, it is hoped to produce surfaces with RMS roughness of approximately 0.25 μm. Another significant obstacle is the need for high intensity beams for data recording. The probability of recording a mark (i.e. causing a local transition of the material from the unwritten to written form) is proportional to the product of the two beams intensities. Typically, very high intensities are needed to alter

the material (on the order of 1.6 GW/cm^2). In addition to fabricating more sensitive materials which are writable at lower laser powers, we are investigating methods to modify the material's energy gap to allow writing at existing laser diode wavelengths. Finally, we are hoping to design materials which can be used for a read/write/erase system. We are presently exploring an exciting class of material which have shown repeated read/write/erase cyclability.

A major concern with the optical system is the ability to dynamically image through various layers of the material. As different planes are recorded in the cube, the magnification and amount of spherical aberration in the system changes. To dynamically compensate for this requires very expensive high performance imaging optics. One way to overcome this obstacle is to fabricate the recording material in a three-dimensional disk format. Using this 3D-CD approach, pages of images are stored as layers in the rotating disk. The addressing beam is again cylindrically focused through the side, while the recorded page of data is imaged into the proper layer of the 3D-CD. Since the disk is constantly rotating, the conjugate planes remain in the same location and the magnification remains constant. In addition, with the use of a properly designed compensator in the input arm, spherical aberrations can be corrected.

A major design issue is the trade-off between data density and parallelism during the recording operation. Due to the parallel nature in imaging spatially modulated beams, whole arrays of data can be recorded at once. Assuming that a 1024 x 1024 SLM is used, it is possible to simultaneously write up to 1 Mb of data. However, as larger data pages are written, the longitudinal distance the addressing beam must remain collimated increases. Unfortunately, since the addressing beam diverges as it propagates, parallel recording results in the need for larger spacing between data planes, and thus, lower data densities. An alternative approach would be to write data in a bit-by-bit fashion allowing the density to be limited only by the Airy spot diameter of the two beams. While this drastically increases the data density, it eliminates the parallel nature of data recording. In Table I, three different data recording formats are presented. In the bit format technique, bits are recorded serially. In the vector scheme, a vector (a column or row) of data is recorded in parallel, while with the image scheme two-dimensional data arrays are recorded at once. Computations are performed assuming Gaussian beam propagation of the addressing beam. The beam width and length are derived from the size of the imaged data array within the cube, while the thickness corresponds to the minimum plane-to-plane spacing of data pages which can be used. Finally, the Maximum Volumetric Density (MVD) correspond to the maximum data density which can be stored within the cube. Note, that going from a bit-by-bit recording format to one in which 1024 x 1024 data arrays are stored in parallel increases the parallelism by 10^6 bits/recording step, but results in a density reduction of 10^4 bits/cm^3. It is important to point out that these calculations neglect aberrations in the input path's imaging system which becomes worse when larger arrays, resulting in larger field angles, are recorded.

| Data Format | Pixel Size P_X x P_y μm x μm | Array Size N_X x N_y | Addressing Beam Dimensions | | | MVD (bits/cm^3) |
			Width $W = P_X N_X$ μm	Length $L = P_y N_y$ μm	Thickness μm	
Bit	1 x 1	1 x 1	1	1	1	1×10^{12}
Vector	5 x 5	256 x 1	1280	5	2	20×10^{9}
	5 x 5	1 x 256	5	1280	33	1.2×10^{9}
Image	5 x 5	16 x 16	80	80	8.2	4.9×10^{9}
	5 x 5	128 x 128	640	640	23	1.7×10^{9}
	10 x 10	1024 x1024	10240	10240	93	0.1×10^{9}

Table 1. The Maximum Volumetric Density (MVD) is shown for various data recording formats.

2.3 Other Techniques   In addition to our work with holographic and two-photon memory, we also have on-going programs in other multi-dimensional optical storage systems. These approaches are all developmentally in a much earlier stage, but all offer significant advantages in terms of capacity, throughput or material cost/fabrication.. *Persistent Spectral Holeburning (PSHB)* allows multiple bits to be written, erased and rewritten in a single location, offering a potential storage density of to 1 Pb/cm^3. The two techniques currently being explored are frequency-domain and time-domain PSHB.

Frequency-domain holeburning involves burning "holes" in a material's absorption band [9]. The ideal material has many narrow, individual absorption lines that blend together into a broad absorption band. When writing information, a frequency-tunable laser is focused to a single spot, modulated and scanned in wavelength. At each wavelength an absorbing center makes the transition from one stable state to another, thus forming "holes" at certain frequencies which indicate the presence of stored bits. This is one-wavelength (non-gated) holeburning. However, since non-gated holeburning tends to be volatile, a second, fixed wavelength is used (gated holeburning) to make the change permanent but still erasable.

Time-domain, or photon echo, holeburning also utilizes spectral holes for memory storage, but relies on coherent optical transient phenomena to store data[10]. Two temporally modulated beams are set to spectrally interfere, and that interference pattern is stored in the form of spectral holes. This concept is spectrally analogous to holograms, which are spatially constructed from the interference between the reference and modulated (object) beam. When a reference beam illuminates the spot for reading, the material emits a delayed coherent output signal that resembles the temporal waveform of the original data pulse.

There are a number of technical challenges to overcome before PSHB becomes viable for storage, however. One issue revolves around how to gate the material; current techniques are unfortunately inflexible or irreversible. Another problem is typical operating temperatures do not exceeded 10 degrees Kelvin, making it difficult and costly to write and maintain data. One particular Rome Laboratory effort is an exception, achieving room temperature holeburning with a novel material, but even this requires considerable development before an acceptable storage density has been attained. These obstacles have slowed PSHB advancement, and have yet to be resolved before any practical applications can be produced.

We are working with researchers at Syracuse University on a promising material, the protein *bacteriorhodopsin (bR)*, for use as a recording material in either two-photon or holographic storage systems. This material is the light transducing protein found in the bacterium Halobacterium halobium. This light harvesting protein is found in the purple membrane of the bacterium. This membrane is essential, protecting the bacteria from the harsh environment of salt marshes where the salt concentration is six times that of ordinary sea water. Bacteriorhodopsin provides the H. Halobacterium the ability to convert light energy to a metabolically useful form when conditions do not allow for aerobic respiration. This flexibility allows the bacterium to switch from photosynthesis to aerobic respiration depending on the environmental conditions. The conditions of the marsh dictate that the protein be resistant to thermal and photochemical damage. These qualities combined with its natural cyclicity (exceeding 10^6) of the protein make it an ideal media for optical recording[11].

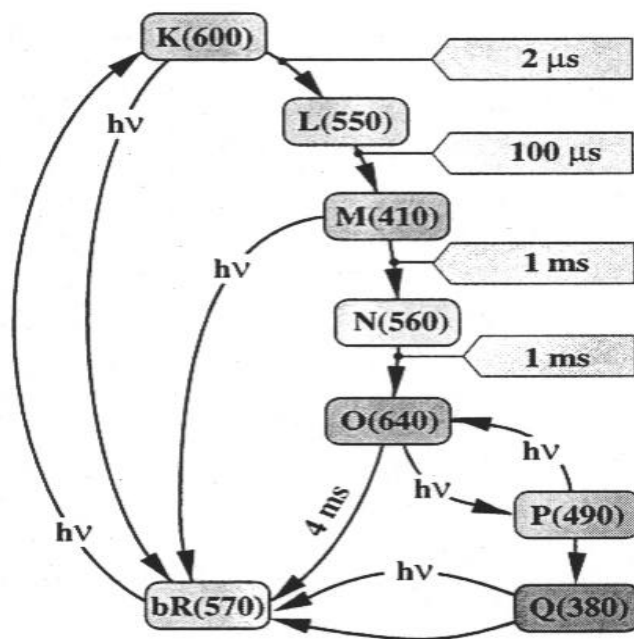The photocycle of bR is shown in Fig. 7. The main photocycle consists of the left-hand side of the figure[12]. In the course of studying this material, a branching reaction was identified. This is identified by the **P** and **Q** states. The resting state of the molecule, the bR state, can be elevated to the **K** state by the primary photochemical event. The other transitions are caused by thermal reactions and result once again in the resting state, bR. The entire photocycle takes about 6-10 milliseconds depending on the temperature. The interesting reaction which creates this branched photocycle happens when the last intermediate state, **O**, is converted by light to **P** which


Figure 7 The photocycle of bR.

subsequently decays to **Q**. **P** and **Q** are the only states involved in the branched reaction and it exists as its own entity to the original photocycle. The **Q** state is the one used for recording data and is created by a sequential one-photon process. This implies that the timing of the reaction must be precisely controlled. The material must be illuminated a second time while the molecules are in the **O** state about 2 ms after the initial writing pulse. The room temperature lifetime of the written state is roughly five years.

The architecture shown in Fig. 8 is used to record on this media. This setup is similar to the architecture of the two-photon approach discussed earlier, with the main difference being that data beam and the addressing beam not only must intersect at a given data plane in the material, but they must follow a timed sequence with the paging pulse activating the media followed by the data pulse 2 ms later changing the **O** state to the **P** state, as shown in Fig. 9.   The entire memory can be bulk thermally erased, or selective page erasure is possible by illuminating with blue light (λ = 413 nm). This wavelength will convert both the **P** and **Q** states back to bR. Alternately, the entire memory can be bulk erased with incoherent light in the 360 - 450 nm range. Some investigators have suggested that the required amount of bacteriorhodopsin for a WORM system capable of
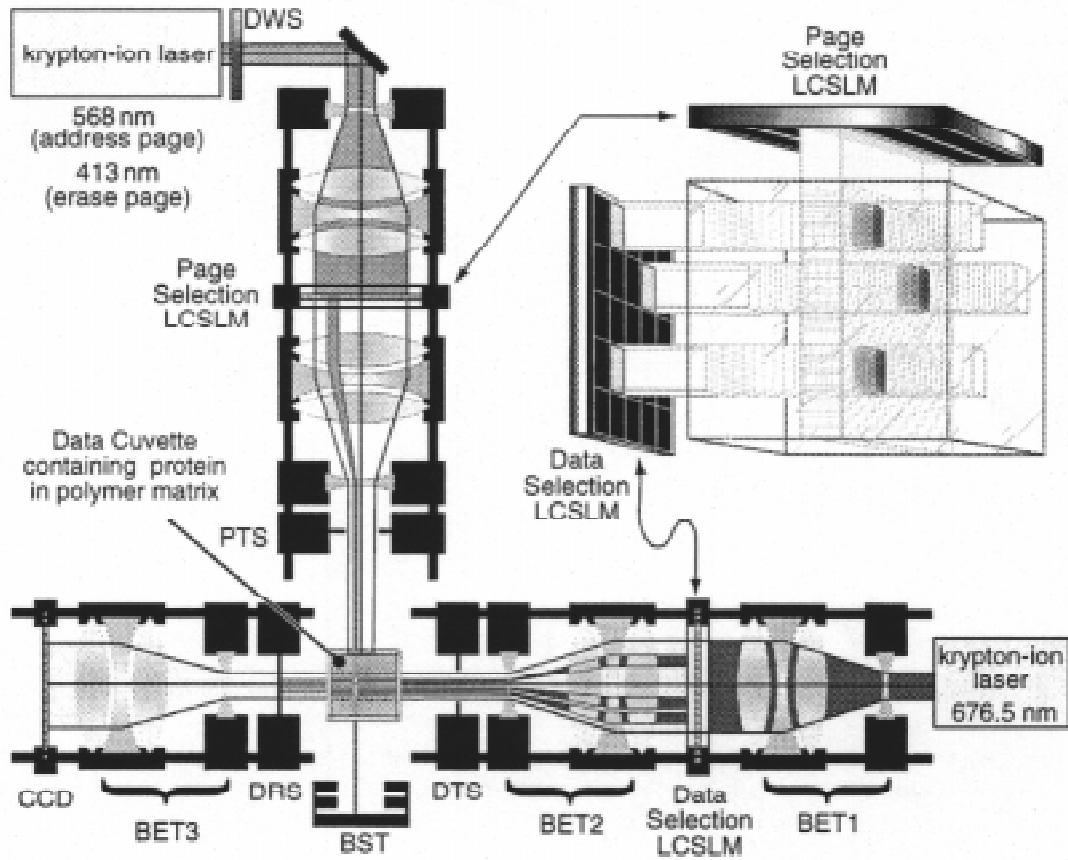
Figure 8 Schematic diagram of the branched-photocycle volumetric memory prototype base on bR.

storing many hundreds of megabytes is on the order of milligrams, and that mass quantities of this material can be made through fermentation processes. Thus, this may ultimately provide extremely cheap memory media. Individual bulk erasures could be provided for those wishing to re-use the media.
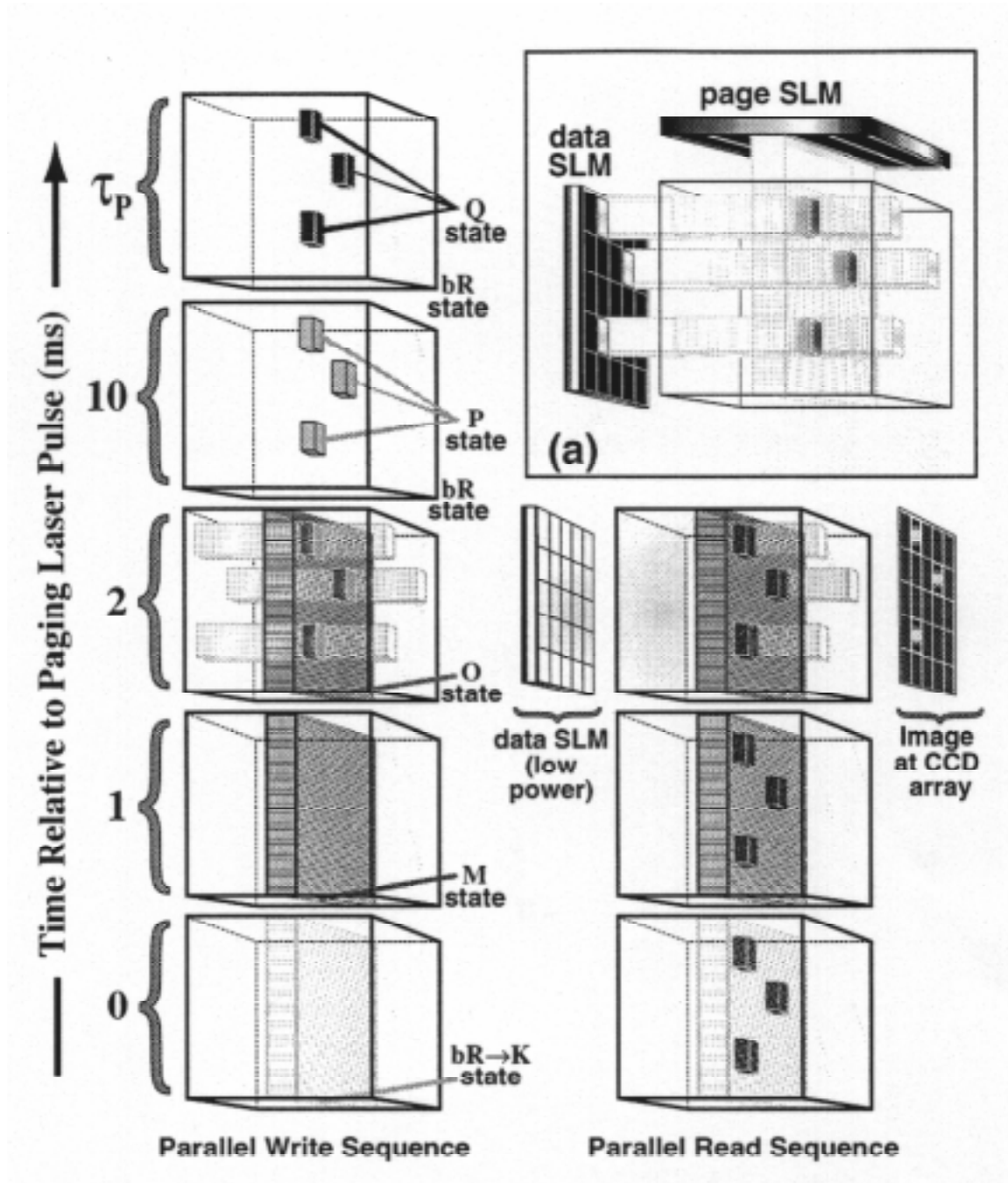
Figure 9 A schematic diagram of the parallel write and read timing sequences, with time progressing from top to bottom.

The 3-D optical storage systems discussed so far represents a fairly new process in the data storage world, but not nearly as new as multi-wavelength **DNA storage**. This approach is based on the use of enhanced deoxyribonucleic acid (DNA) polymers as the three dimensional structure in prototype optical volumetric memories[13]. DNA polymers provide a robust and programmable synthetic material that can be organized into a wide variety of pre-determined structures. Due to the precise geometric and distance requirements of Förster energy transfer, which allows for the use of a single wavelength excitation wavelength and multiple wavelength emissions during the write process, energy is transferred at the molecular level, allowing for almost 100% quantum efficiency. Organized DNA chromophore structures, both natural and synthetic, produce relatively intense sub-micron fluorescent light sources. The intensity levels in the synthetic structures are within the range of commercially available detectors. The development of a customized optoelectronic read/write system is presently a primary research objective to make a practical DNA optical memory.

Working with Nanotronics, Inc, in San Diego, DNA polymers have been successfully attached to glass, aluminum and silicon, to determine compatibility for use in a practical solid architecture in future systems. DNA chromophores exhibited energy transfer properties when attached in the solid state comparable to their solution state, and they exhibited quenching properties in the solid state dramatically superior to properties in a solution state. Experiments demonstrated the potential for multiwavelength optical storage material using DNA polymers, the early efforts demonstrated a six color response. Ongoing efforts show optical data storage using this organic material will allow very high data density, on the order of 100 bits/micron (100 times the lateral storage density of present storage devices). A conceptual DNA storage device is shown in Fig. 10. As more devices shrink in size, synthetic DNA will be a major player in future technologies which require nanotechnology.
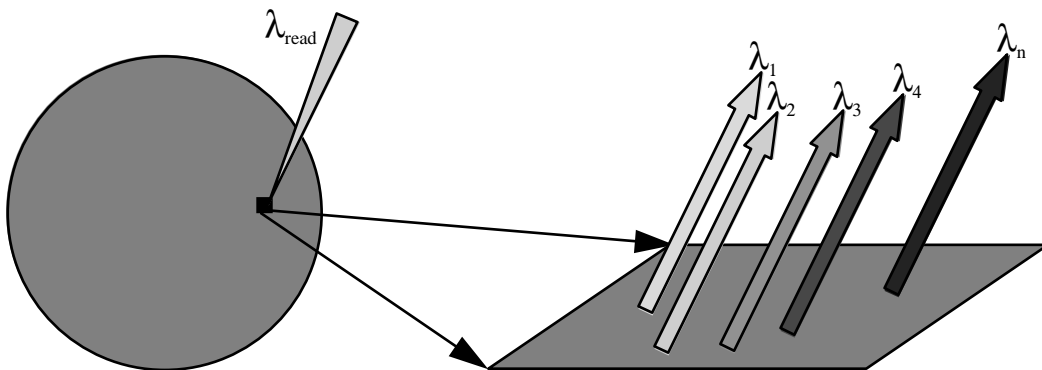
Figure 10 Multi-spectral output from a recorded spot in DNA material.

3.0 Summary and Conclusions

In summary, the technologies described here have potential in all three memory requirements; primary, secondary, and tertiary. Three-dimensional optical memory development can be applied to the secondary and tertiary memory requirements offering large data capacities, medium access time, and archivability. The 3-D optical memory concepts with terabit capacities, gigabit throughput rates, and 10-nanosecond access times are potential solutions to the primary and secondary memory requirements.

With our two-photon and holographic work we have developed working demonstration systems, and anticipate operational systems within the next few years. Unfortunately, the prospects of a future system are still somewhat limited by key system components such as SLM's, fast (non-mechanical) beam deflectors, two-dimensional error correction and detection encoders/decoders and dynamic focusing/aberration control. However, these systems ultimately offer the advantage of extremely high data densities, and reasonable data I/O rates due to the parallel nature of data recording/readout. We are also pursuing more elaborate techniques and materials such as spectral holeburning and DNA recording systems and bacteriorhodopsin as a recording medium. These techniques represent technologies which may be further from maturation, but represent significant progress in mass data storage technology.

References

1. Haritatos, Fred N., "High Performance Optical Disk Systems," SPIE/OSA Optical Data Storage Conference, Feb. 1991.

2. Haritatos, Fred N., "Optical Recording," Defense Electronics, vol. 25, no. 10, Sept. 1993.

3. Haritatos, Fred N., "High Performance Optical Disk Systems for Tactical Applications," IEEE, May 1991.

4. Burr, G., Mok, F., Psaltis, D., "Large-Scale Holographic Memory: Experimental Results," SPIE Proceedings, vol. 2026, p. 630-641, 1993.

5. Mok, F.H., "Angle-Multiplexed Storage of 5000 Holograms in Lithium Niobate," Optics Letters, vol. 18, no. 12, p. 915-917, June 1993.

6. Burr, F. Mok, D. Psaltis, Large-Scale Holographic Memory: Experimental Results, SPIE Proceedings, vol. 2026, 1993, p. 630-641.

7. Esener, S., Fainman, Y., Ford, J.E., Hunter, S., "Two-Photon Three-Dimensional Memory Hierarchy," (Photonics for Computers, Neural Networks and Memories, San Diego CA, 22-24 July 1992), Proceedings of the SPIE-The International Society for Optical Engineering 1993, 1773, p. 346-355, 1993.

8. Dvornikov, A.S., and Rentzedis, P.M., "Two-Photon 3-D Optical Memory," IEEE Proc. of 1994 Conference on Solid State Memory Tech., p. 109-118, 1994.

9. Maniloff, E., Altner, S., Bernet, S., Graf, F., Renn, A., Wild, U., "Spectral Hole Burning Holography in Optical Memory Systems," SPIE Proceedings, vol. 2026, p. 592-603, 1993.

10. Babbitt, W.R. and Mossberg, T.W., "Time-Domain Frequency-Selective Optical Data Storage in a Solid State Material," Optical Communications, vol. 65, p. 185, 1988.

11. Horspool, W., Song, P, *CRC Handbook of Organic Photochemistry and Photobiology*, CRC Press, Boca Raton, Chap. 33, 1995.

12. Birge, R., "Protein-Based Branched Photocycle Three-Dimensional Optical Memories," Rome Laboratory Final Report F30602-93-C-0135, 1996.

13. Heller, M., Tu, E., "DNA Optical Storage," U.S. Patent Application, Pending.