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16. Abstract High capacity, high transfer rate, random access memory systems are needed to archive and distribute the tremendous volume of digital information being generated, for example, the human genome mapping and online libraries. The development of multi-gigabit per second networks underscores the need for next-generation archival memory systems. During Phase I we conducted the theoretical analysis and accomplished experimental tests that validated the key aspects of the ultra-high density holographic data storage module with high transfer rate. We also inspected the secure nature of the encoding method and estimated the performance of full-scale system. Two basic architectures were considered, allowing for revertible compact solid-state configuration with limited capacity, and very large capacity write once read many memory system.				
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PURPOSE OF RESEARCH

The overall goal of this project is to develop a digital data storage device that has ultra-high storage density, capacity and throughput and encrypted data access, and to demonstrate the feasibility of building the prototype Memory Module. The novelty of the proposed storage device is based on three-dimensional recording of the holograms in photorefractive media (ferroelectric or photopolymer) using a new encoding/decoding technique referred to as Speckle Encoded Reference Wave (SERW). Three-dimensional speckle wave multiplexing maximizes storage density while providing an efficient and practical method for data retrieval and secure data access. This technique enables ultra-high storage density, high-speed data transfer, and random and secure data access. The specific goals for Phase I were to develop an analytic model of the speckle-encoded holographic memory in solid-state configuration, with high throughput and secured access, perform experimental tests to validate the model, demonstrate operation of a scaled memory device and estimate the performance of a full-scaled memory.

DESCRIPTION OF RESEARCH CARRIED OUT

New data storage technologies are required to sustain the increasing volumes and rates of data generation and to meet the demands of high throughput networks. Although two major surface storage techniques (magnetic and optical) have accelerated their roadmaps to increase the surface density and storage capacity, their technology (or cost) limits are in the 10^{11} b/cm² range^{1,2}. Thus, alternative storage technologies, and in particular optical technologies, effective in providing a greater storage density and capacity at reasonable cost, are required^{3,4,5}.

Holographic memory has been a subject of interest for decades since it was first suggested by van Heerden⁶. High information density, parallel access and high-speed retrieval are among the features that make this technique of data storage so attractive. Selective properties of volume holograms due to angular^{7,8} or wavelength deviation⁹ from the Bragg conditions, as well as reference beam phase encoding¹⁰ are the methods frequently used for data input and retrieval. The combination of reference beam phase encoding with spatial-shift multiplexing was shown to be an efficient approach for high-density holographic information storage.^{11,12} A similar technique with many plane wave reference (or spherical wave) beam encoding was suggested and experimentally demonstrated.¹³ Although all these methods allow storing the holograms with high density, the longitudinal shift component of the recording media has not been considered for coding the individual "pages" of information. In contrast, the recently discussed method of multilayer optical storage^{14,15} makes it possible to record the information at different depths within the media similar to that of a magnetic disc stack which are currently used in PC's. It was demonstrated¹⁶ that thin layers of a holographic recording in the volume media can provide a high information storage capacity and fast data transfer rate.

Our work is unique in that we have demonstrated the possibility of building a single volume, multilayer holographic optical memory using a speckle reference beam. The novel features of using a speckle-encoded reference beam to multiplex holograms are that: 1) there is high shift and angular selectivity in any direction within the recording plane, 2) shift selectivity exists in the longitudinal dimension, 3) image brightness decreases uniformly and no phase distortions are introduced at shift detuning, and 4) phase pre-encoding can be used to build a solid-state memory system. These features lead to the possibility of building a robust, large capacity, high data rate, memory system.

During Phase I of this project, we successfully demonstrated the possibility to build a memory module with solid-state architecture; however, discussions with technical personal of DOE during the kickoff meeting and the technical results brought us to a common understanding that a high capacity memory unit that can form a compact, fast access, archiving complex (SILO) is of primary interest to DOE. Based on the Phase I results, we estimate an ultimate memory module capacity of 10^9 holograms (= 1000 terabits or 10^{15} bits) in one CD-ROM format disc, allowing for data transfer rates of 1 Gigabit per second (access

times of 1ms), and a robust architecture. Current media limitations may reduce this number 1-2 orders of magnitude; however, we anticipate that during this project, we will develop an improvement in the characteristics of current recording media which will allow us to approach the fundamental limits of optical data storage systems.

Detailed Phase I Results

Background

Holographic storage extends the high density of the optical disk (CD ROM, DVD) into a true, three-dimensional random access parallel/multiple transfer system. High information density, parallel access, and high-speed retrieval are among the features that make this technique of data storage so attractive.

In volume holographic storage, a two-dimensional image (data page) is recorded using a reference beam adjustment that can be considered as its coding. The beam encoding can be by varying its parameters, i.e., the wavelength, propagation angle or by amplitude-phase modulation of its wavefront. By re-illuminating the recorded hologram with the original reference beam, the entire two-dimensional image is recalled. (It was also demonstrated¹⁷ that three-dimensional image recording and reconstruction is also possible.) Parallel data access that allows for recall of an entire data page simultaneously, results in very high data rates. In addition, holographic data storage has ultra high density with its theoretical limit of 10^{12} bits/cm³).

Our proposed design of a novel holographic memory uses the **SERW** technique which maximizes storage density. Holograms can be encoded by physically shifting the recording medium with respect to the speckle wave or by encoding the phase of the speckle reference beam. These two architectures are shown in **Figure 1a**, where holograms have been spatially multiplexed upon the surface of a disk-like memory carrier, and **Figure 1b**, where phase encoding is used in a compact, solid-state system. In each system, parallel recall of a 1024 x 1024 bit image is achieved, which is equivalent to having a 1 Mbit wide data bus. Shifting the medium, similar to a rotating disk design currently used by CD ROM, results in ultra-high data capacity owing to the use of a large media substrate, while phase encoding results in a robust, "no-moving parts" system (of somewhat lower capacity). At modest address speeds of 1 kilohertz, data rates of close to 1 Gbit/second can be achieved, which is ~ 100 times faster than the current computer hard drives. Thus, the holographic memory provides ultra-high data capacity as well as high-speed data transfer.

Figure 1. Two implementations of the holographic memory concept. a) Shift-multiplexing with a speckle reference beam allows each data page to be stored ~ 3 microns apart on a disk structure. b) Phase encoding by a SLM permits design of a rugged, solid-state system with a somewhat reduced capacity. Reconstruction of each data page accesses as much as 1 Mbit simultaneously. Total device capacity can exceed 10^{15} bits for a CD ROM type of disk.

Theoretical analysis

We consider the volume hologram formed by a plane signal wave $S_o(r) = \exp[ik_s r]$ and **SERW** with a complex amplitude of $R_o(r)$ and angular divergence of $\Delta\theta_{sp}$ (see **Figure 2**). For the convenience of the analysis, **SERW** propagates normally to the recording media front surface and the $S_o(r)$ -wave has an incident angle of θ_o ($k_s = k_o \{\sin\theta_o; \cos\theta_o\}$, $k_o = 2\pi/\lambda$). The illuminated area of the diffuser is $P(q)$, ($q = \{x, y\}$), and a fully developed speckle pattern¹⁸ is formed at the distance $z_{DH} \ll D$. We suppose that the following relationships^{19,20} between the thickness T of the hologram and recording geometry are satisfied:

$$T \gg \lambda/(\Delta\theta_{sp})^2 \geq \lambda/\theta_o. \quad (1)$$

It is important, for further analysis, to fulfil the ratio in Eqn. (1) that can be expressed in terms of the ratio between the average longitudinal speckle size $\langle\sigma_{||}\rangle$, holographic fringe spacing Λ ($\Lambda \sim \lambda/\theta_o$), and the thickness T of the hologram. Thus, Eqn (1) describes the conditions, when the thickness of the hologram T is larger than spacing Λ , covering several speckle lengths $\langle\sigma_{||}\rangle$. In this case only one “-1” diffraction order will be reconstructed from the hologram and the low light-scattering conditions can be satisfied²⁰.

Figure 2. SERW-hologram recording geometry.

The hologram is recorded when the light-sensitive medium with the initial permittivity ϵ_m is exposed with the interference pattern $E_o(r) = S_o(r) + R_o(r)$. This generates the spatial modulation of $\tilde{\epsilon}(r)$ in the following form:

$$\tilde{\epsilon}(r) = \epsilon_m + \delta\epsilon(r) = \rho |E_o(r)|^2, \quad (2)$$

where the magnitude of the modulated component of permittivity $\delta\epsilon(r)$ is small as compared to ϵ_m , i.e., $\delta\epsilon(r) \ll \epsilon_m$, and ρ is the recording medium parameter. The amplitude $S(r)$ of the diffracted beam in the first Born approximation beam $|R(r)| \gg |S(r)|$ can be found as^{21,22}:

$$S(r) = -\frac{\rho k_o^2}{n_o} \int_{-\infty}^{\infty} P(r) \delta\epsilon(r) R(r) G(r, r') d^3 r. \quad (3)$$

Here $G(r, r') = \exp\{ik_o |\mathbf{r} - \mathbf{r}'|\} / 4\pi |\mathbf{r} - \mathbf{r}'|$ is the Green's function.

We now assume that after its recording, the hologram is illuminated with the same **SERW**, but its mutual spatial position is altered on the distance $\Delta(r)$. Such spatial shift leads to spatial decorrelation between the structure recorded in the volume of the hologram and speckle pattern in the reconstruction **SERW**. As the last one remains essentially the same, the reconstruction beam $R(r)$ after shift operation can be described as $R(r) = R_o(r + \Delta)$, where $\Delta = \hat{x}\Delta_x + \hat{y}\Delta_y + \hat{z}\Delta_z$ is the vector of spatial displacement with its lateral

$\Delta_{\perp} = \sqrt{\Delta_x^2 + \Delta_y^2}$ and longitudinal $\Delta_{||} = \Delta_z$ components.

Taking into account that in Eqn. (3) the modulation $\delta\epsilon(\mathbf{r})$ is proportional to the product $R_o^*(\mathbf{r})S_o(\mathbf{r})$, the normalized diffraction efficiency η_N that is the ratio of the diffraction beam intensity at its shifted state to its original value at $\Delta = 0$ can be expressed as:

$$\eta_N = \frac{I_s(\mathbf{r}, \Delta)}{I_s(\mathbf{r}, \Delta = 0)} = \frac{\left| \int_{-\infty}^{\infty} P(\mathbf{r}') R^*(\mathbf{r}') R_o(\mathbf{r}') d^3 r' \right|^2}{\left| \int_{-\infty}^{\infty} P(\mathbf{r}') R_o^*(\mathbf{r}') R_o(\mathbf{r}') d^3 r' \right|^2}, \quad (4)$$

where $I_s(\mathbf{r}, \Delta) = |S(\mathbf{r}, \Delta)|^2$ is the diffracted beam intensity.

On the other hand, if the condition of the central-limit theorem of statistics is fulfilled and the complex amplitude $R(\mathbf{r})$ is the complex Gaussian random variable at each local point of the space (x', y', z') the integration over lateral coordinates in Eqn. (4) can be replaced by averaging over the ensemble, and therefore

$$\iint_{\mathcal{S}} R^*(\mathbf{q}', z_o) R_o(\mathbf{q}, z_o) d^2 q = \langle R^*(\mathbf{q}', z_o) R_o(\mathbf{q}, z_o) \rangle, \quad (5)$$

where $\mathbf{q} = f(x, y)$. This product on the right side of Eqn. (5) is known as the mutual intensity of the speckle pattern. It is equivalent to the autocorrelation function of light intensity distribution described as $C_R(\mathbf{r}, \mathbf{r}') = \langle I_R(\mathbf{r}) I_R(\mathbf{r}') \rangle$, when the conditions of slowly varying average intensity in the speckle pattern $\langle I(\mathbf{r}) \rangle$ are satisfied. However, it is more convenient in practice to measure the complex correlation function $\mu(\mathbf{r}, \mathbf{r}')$ that can be introduced as:

$$\mu(\mathbf{r}, \mathbf{r}') = |J(\mathbf{r}, \mathbf{r}')|^2 / |J(\mathbf{r}, \mathbf{r}) J(\mathbf{r}', \mathbf{r}')|. \quad (6)$$

Then in a Fresnel's approximation, Eqn. (6) for $\mu(\mathbf{r}, \mathbf{r}')$ will be written as:

$$\mu(\mathbf{r}, \mathbf{r}') = \frac{\left| \iint_{\mathcal{S}} |P(\mathbf{q})|^2 \exp[i\tau(x^2 + y^2) + i(\alpha x' + \beta y')] dx' dy' \right|^2}{\left| \iint_{\mathcal{S}} |P(\mathbf{q})|^2 dx' dy' d\mathbf{z}' \right|^2}, \quad (7)$$

where $\alpha = (2\pi/\lambda z_o^2)(z\Delta_{\perp} - x\Delta_{\parallel})$; $\beta = (2\pi/\lambda z_o^2)(z\Delta_{\perp} - y\Delta_{\parallel})$; $\tau = \pi\Delta_{\parallel}/\lambda z_o^2$.

Now let's analyze the effect of spatial decorrelation between the SERW and the structure recorded in the volume of the hologram on the efficiency of the interaction. The experimentally controlled parameter in this case is the diffracted beam intensity $I_D = |S|^2$ and therefore it is convenient to introduce the relative diffracted beam intensity $I_{DN}(\Delta) = I_D(\Delta)/I_{D(\Delta=0)}$, where the measured diffracted beam intensity $I_D(\Delta)$ is normalized by its peak value at zero lateral shift $I_{D(\Delta=0)}$. With three-dimensional correlation function $\mu(\mathbf{r}, \mathbf{r}')$ in the form of Eqn. (7), and using the Fresnel-Kirchhoff diffraction integral, the dependence $I_{DN}(\bar{\Delta})$ is as:

$$I_{DN}(\Delta_{\perp}) = \frac{I_D(\Delta_{\perp})}{I_{D(\Delta_{\perp}=0)}} = \frac{\left| \int_0^T \exp\left[\frac{ik_o n \Delta_{\perp}^2}{2d_{\perp}}\right] \iint_{-\infty}^{+\infty} |P_D(\bar{q})|^2 \times \exp\left[-\frac{ik_o n}{d_{\perp}} \bar{q} \bar{\Delta}_{\perp}\right] d^2 q d\mathbf{z} \right|^2}{T^2 \times \iint_{-\infty}^{+\infty} |P_D(\bar{q})|^2 d^2 q}, \quad (8)$$

where n is refractive index of the recording medium, d is the distance between the hologram and diffuser, and $P_d(q)$ is the cut-off function that determines the diameter of the illuminated part of the diffuser.

It follows from Eqn. (8) that any spatial mismatch between the hologram and reconstruction beam $R(r)$ should result in a decline of the diffracted beam intensity.

Figure 4 shows the fall-off in $I_{DN}(\Delta_L)$ that occurs for lateral shift ($\Delta_{||} = \text{const}$) calculated from Eqn. (8) in conditions that are close to experimental, (i.e., $\lambda = 515 \text{ nm}$, $T = 3 \text{ mm}$, $n = 2.2$ for LiNbO_3 crystal, $d = 200 \text{ mm}$, $P_d(q) = 3 \text{ mm}$). The dashed line in this figure comes from the calculation of the correlation function of the speckle pattern²³ for identical conditions.

Figure 3. Shift selectivity $I_{ND}(\Delta_L)$ calculated from Eqn. (8) .

Moreover, as the speckle pattern has central symmetry, this type of selectivity occurs at any direction of the lateral shift in the XY plane. Illustrating this fact, **Figure 4a** displays a very symmetrical fall-off of the diffracted beam intensity upon a increasing lateral shift Δ_L .

Figure 4. Diffracted beam intensity $I_N(\Delta)$ as a function of lateral Δ_L (a) and longitudinal $\Delta_{||}$ (b) shift.

Then, since the speckle pattern has a three-dimensional nature, the longitudinal shift also results in spatial decorrelation between the hologram and reconstruction **SERW**, and thus a third dimension can be used to multiplex the information. By analogy to $I_{DN}(\Delta_L)$, the diffracted beam intensity $I_{DN}(\Delta_{||}) \rightarrow 0$, when the shift distance $\Delta_{||}$ exceeds the longitudinal correlation length $\langle \sigma_{||} \rangle$ (see **Figure 4b**), and thus the possibility to implement several “virtual layers” of holograms within the same volume of the recording media exists.

Construction of breadboard memory system

To experimentally verify the proposed memory system concept, a breadboard system was constructed as shown in **Figure 5**. It was set on a 4' x 8' vibration isolated table. A model 2020 Spectra-Physics CW argon ion laser was used as the coherent light source in these experiments. Its output beam (at $\lambda = 515 \text{ nm}$) was expanded to 1 cm with the telescope formed by Spatial Filter and Lens-1. A two-shoulder recording scheme was formed with the beamsplitter and mirror directing the object and reference beams. The combination of the Phase Mask (ground glass plate) and Condenser Lens was used to generate the speckle pattern with the needed average lateral speckle size $\langle \sigma_1 \rangle$ in intervals from 3 to 20 μm at the recording medium plane. The speckle reference beam and signal beam, intersected at an angle of $\theta_o = 35^\circ$ ($\theta_{Ro} = 0^\circ$).

Figure 5. Breadboard for holographic data storage with SERW.

SERW holograms were recorded in a 2.8-mm-thick Fe-doped (0.02% Fe/mol) LiNbO_3 crystal and ULSH-500-2B photopolymer using 3-D shift multiplexing. The recording material, with its front surface perpendicular to the incoming speckle beam, was set onto a XYZ computer-controlled positioning table, which had a precision of 0.025 μm in the X, Y, and Z planes. The diffracted beam intensity was measured with the calibrated PIN-photodiode. Diffraction efficiency of the recorded hologram in its original position ($\Delta_L = 0$) was approximately 10^{-3} .

The characteristics of the photo-detector (a PIN-diode in our setup) is an important part of the breadboard design, as it is used to measure the diffracted signal intensity and its variation when the spatial position (or spatial structure) of SERW is modified as compared to the initial conditions at recording stage. Taking into account the wide range in the variations of the diffracted signal intensity I_Δ due to reconstruction speckle pattern alteration (speckle de-correlation), special measures were taken to provide a properly calibrated receiver that correctly covers the entire interval of the measured data. The typical dependence of the output signal versus incoming laser power is shown in **Figure 6**, illustrating linear characteristic in a wide interval (about 10^4) of the measured intensity variations.

Figure 6. Calibration curve for the photo-detector.

Finally, **Figure 7** illustrates an area-view of the experimental setup used to study the spatial-shift characteristics of the speckle encoded reference beam hologram.

Figure 7. Experimental setup of holographic memory with SERW.

Experimental result: Lateral shift multiplexing

Experimentally measured dependence of “*shift selectivity*” (which is the normalized diffracted beam intensity I_{ND} upon the spatial shift Δ_L) is shown in Figure 8 for several values of the estimated average speckle size $\langle \sigma_L \rangle$. It is evident from this figure that every time the spatial shift is introduced between the hologram and speckle pattern, the diffraction signal intensity declines, achieving its minimal value at Δ_L

very close to $\langle\sigma_{\perp}\rangle$. Thus, the parameter “*relative shift selectivity*” can be introduced, that is $\Delta_{\perp}/\langle\sigma_{\perp}\rangle$ and allows for studying the major dependencies of speckle selectivity in general, regardless of the real size of speckle $\langle\sigma_{\perp}\rangle$.

Figure 8. Shift selectivity of SERW hologram for $\Delta_{\perp} = 8 \mu\text{m}$ (a) and $16 \mu\text{m}$ (b).

Typical examples of such characterization are presented in Figure 9 and Figure 10, where the diffraction signal intensity is shown as the function of relative shift for several values of the initial diffraction efficiency η and holographic fringe spacing Λ . In both cases, $I_{\text{ND}}(\Delta_{\perp})_{\eta}$ and $I_{\text{ND}}(\Delta_{\perp})_{\Lambda}$ the measured value of shift selectivity does not depend upon initial value of η or Λ .

Figure 9. Relative shift selectivity of SERW hologram versus initial diffraction efficiency.

Figure 10. Relative shift selectivity of SERW versus recorded grating spacing Λ .

The data presented above should be considered as an important result, as it states that beside uniform intensity decline with incrementing shift, no variations in the reconstructed image (data-page) characteristics should be observed with spatial shift between the holographic memory module and SERW. The same observation is also correct for different spatial frequency of the recorded images, as no dependence of $I_{\text{ND}}(\Delta_{\perp})$ at a different Λ .

To demonstrate the data multiplexing in one memory volume, a spatial shift of $\Delta_L = 10 \mu\text{m}$ was introduced between exposures to record multiple pages of information. We prefer to use the long spatial shift decorrelation condition $\Delta_L (= 10 \mu\text{m}) > \langle \sigma_L \rangle (= 3 \mu\text{m})$ in order to better observe the low noise reconstruction. During reconstruction, proper mutual re-positioning of the hologram and the reference speckle beam resulted in information retrieval. Diffracted beam intensity was measured using a pin photo-detector. A typical sequence of 30 holograms recorded in the form of a 6×5 -matrix is shown in **Figure 11**. The scan step-length for this matrix reconstruction was $0.25 \mu\text{m}$. Notice the symmetric nature of the selectivity in both the X and Y directions that is characteristic of using speckle reference waves. The measured speckle selectivity agreed well with previous calculations and correlates with the results of the theoretical analysis (see **Figure 4**).

Figure 11. Reconstructed intensity map from 30 holograms recorded as a 5×6 matrix.

b. Longitudinal shift multiplexing

After the first layer L_1 recording was completed for the next layer L_i which was formed by shifting the diffuser that generated the speckle pattern along the central axis of the speckle beam propagation. The shift magnitude, as discussed before, should satisfy the condition $\Delta_{||} \geq \langle \sigma_{||} \rangle$, which, in our experimental setup, was on the order of $\Delta_{||} \approx 30 \mu\text{m}$. In this way, the new layer L_2 was created with lateral shift selectivity and a new matrix of $n_{L_2} \times m_{L_2}$ where holographic “pages” were recorded. **Figure 12** shows the reconstructed intensity map of two holograms stored in the crystal by shifting in the z direction by $40 \mu\text{m}$. These two diffracted signals were recorded and reconstructed using the effect of longitudinal shift selectivity of the volume hologram with the reference speckle wave.

Figure 12. Reconstructed holograms in two (2) subsequent layers recorded with a longitudinal shift of 30 μm .

Data Storage and Retrieval

The breadboard was modified to permit images to be input via transparencies and read-out using the 356 x 292 pixel VV5404 CMOS sensor. The advantage of having this type of detector instead of a standard CCD is smaller pixel size of CMOS that, according to the vendors, can be as small as $1 \times 1 \mu\text{m}^2$. Also, CMOS has almost 100 times less power consumption than the CCD. Another advantage of CMOS detectors is direct access to the pixels, which can improve the post-processing operation. **Figure 13a** shows an example of several images recalled from the memory module.

Figure 13. Reconstructed images (a) stored in holographic memory with $\Delta_L \approx 10 \mu\text{m}$ (a), and an example of the data recall with CMOS system at retrieval rate of 10 msec (b) and $\Delta_L \approx 5 \mu\text{m}$ (b).

Similar to **Figure 11**, a shift distance of $\Delta_{\perp} = 10 \mu\text{m}$ in the lateral direction was used for each data-page (image) for storage and retrieval. The information content of the images was found to have a negligible impact on shift selectivity that corresponds to data from **Figure 9** and **Figure 10**.

On the other hand, no changes were observed in the phase distribution of the reconstructed beam upon incremental lateral shift. This is an important result, as it allows us to consider the back-loop, self-adjustable system in conditions when exact matching occurs between the recorded and reconstruction fields.

Each data page in **Figure 13a** contains significant amounts of information ($\sim\text{Mbit}$), which results in ultra-high data transfer rates. Within this project, the real-time data page recall and transfer was fulfilled. A typical example of the information retrieval is demonstrated in **Figure 13b** where the sequence of the pulses corresponds to the recalled data pages. The multiplexed holograms of about 103 Kb each were retrieved and transferred with the rate at $\sim 10 \text{ msec}$. A typical reconstructed image is shown in the right corner of **Figure 13b**. In these experiments, the parameters of the CMOS detector (356×292 pixels) were the limiting factor for page density.

Security data access

In the majority of the holographic memory systems, one of the fundamental problems of the data storage capacity is the noise related to the crosstalk, which is generated through diffraction of the reconstruction beam on the adjacent holograms. This effect is particularly strong when the character of the selectivity exposes regular intensity modulation (sidelobes), as this is the case of the angular or spectral multiplexing. The SERW multiplexing has essentially a different nature. As it was shown above (in Eqn. (3) and **Figure 4**) in the SERW configuration, the diffracted signal intensity rapidly decreases upon the magnitude of spatial decorrelation with no sidelobes. It also follows from Eqn. (4) that the character of the shift selectivity is basically determined by the orthogonality of the recorded and reconstructed fields, and once this condition is satisfied, the reconstruction of the hologram with a non-eigen encoder is impossible. **Figure 14** shows a typical example of shift selectivity in the X and Y directions, where the diffracted beam intensity decreases smoothly upon shift with no ripples within three orders of the magnitude. For comparison, the solid lines in this figure illustrate typical behavior of the angular selectivity with its strong intensity variation and therefore strong crosstalk.

Figure 14. Shift selectivity of the hologram.

We also performed a set of experiments to prove the concept that the hologram recorded with SEWR can be recalled only with exactly the same spatial structure of the beam, and in particular with the same amplitude-phase distribution of the reconstruction pattern. After the data page was recorded with the Phase-Mask-1 (see **Figure 5**), the new, different Phase-Mask-2, was introduced into the pathway of the reference beam. No signal was observed with an intensity increase in the reconstruction beam over 30 times.

It is clear that because the spatial amplitude-phase distribution of the speckle pattern is very unique in every location of its 3-D space, the spatial correlation between its two random positions or between two different speckle patterns is extremely low. We can estimate the security level in a non-authorized data accesses from the following factors: With typical size in the spatial structure of the encoder on the order of 0.5 microns and its aperture equal to 1 cm, the total number of spatial locations could be $\sim 10^9$. In a most simple case of binary phase encoding of locations with 0 and π shift (the current technique allows us to achieve more than eight (8) phase levels). The possible number of random combination will be equal to $N = 2^{(10^9)}$, which is nearly infinite. Therefore, the probability of an intruder synthesizing a mask without access to the original one is zero. Thus, the speckle generator (fabricated on a quartz substrate) can be used as an extremely secure access key. An interesting property of the SERW architecture is that many users can store and retrieve data on the same memory system without having access to each other's data. Therefore, many security levels can exist within a single system. Because the security lies in the actual physical hardware of the system, it is not possible for software hackers to gain access. This is the fundamental difference from other forms of data security systems. To demonstrate this security feature, we stored several different data-pages almost at the same location of the crystal, but used two different speckle pattern generators (diffusers). An important condition to be satisfied at these experiments was that both encoders generated the speckle pattern but with a different Gaussian statistic. At the retrieval stage, only the data page that corresponded to its original generator could be recalled.

Solid-state architecture and phase pre-encoding technique

It was shown in the *Background Section*, that the diffracted beam amplitude, when the speckle reference beam is used for reconstruction, depends upon the spatial correlation function between the recording R_o and reconstructing R reference beam structures. When these two structures are orthogonal, the diffracted signal is zero. In coherent optics, the most typical example of the orthogonal functions would be the amplitude-phase distribution from different transverse laser modes - for example, the TEM_{00} and TEM_{01} modes are orthogonal. As an example, we consider the modes of a confocal laser cavity for the recording-reconstructing field spatial distribution. These modes can be written as

$$R_i(q, \varphi) = C_{pi} E_{pi}(q) \cos(l, \varphi), \quad (9)$$

where $E_{pi}(q) = \left(\sqrt{2q} / \rho_R \right)^l L_p^l \left(2q^2 / \rho_R^2 \right) \exp \left(-q^2 / \rho_R^2 \right)$, q and φ are the polar coordinates, C_{pi} is the normalizing coefficient, ρ_R is the laser beam diameter in the plane of the hologram, and $L_p^l(a^2)$ is the Laguerre function. For laser modes with different indices, Eqn. (9) then can be transformed into²⁵:

$$S(\vec{q}) = S_o(\vec{r}) \exp[ik_0 \sin \theta_s] \times C_{pi} C_{mn} H(\ell) \frac{\rho_R^2}{2} \int_0^{D/2} q' \exp(-q) L_p^l(q) L_m^l(q) dq \quad (10)$$

where

$$H(\ell) = \begin{cases} \pi, & \text{for } \ell = 0; \\ 2\pi, & \text{for } \ell \neq 0. \end{cases}$$

Because the Laguerre functions of different (p,m) indices are orthogonal, it follows from Eqn. (10) that the diffracted signal amplitude $S(q)$ falls to zero if different transversal laser modes are used at the recording and reconstruction steps.

In another set of the experiments, the variation of the mode structure of the laser beam altered the spatial distribution of the complex amplitude of the beam that illuminated the speckle-encoder. This operation can be achieved by altering the laser cavity parameters. As was demonstrated in the first technical report, such an operation leads to formation of the beams with orthogonal distribution of their complex amplitude. A typical example of the complex amplitude spatial distribution $A(x)$ for two fundamental laser modes TEM_{00} and TEM_{01} is shown in Figure 15.

Figure 15. Complex amplitude distribution for two fundamental laser modes.

The laser modes are described by the Laguerre polynomials. Therefore, when the hologram is recorded with mode TEM_{mn} its reconstruction, with any other non-equivalent mode TEM_{kl} where its amplitude is orthogonal to TEM_{mn} should result in strong decrease of the diffracted signal intensity. The typical results of the experimental realization for such operation are demonstrated in Figure 16.

Figure 16. Hologram recording and reconstruction with the orthogonal modes.

Here, Row A corresponds to the recording (1A) and reconstruction (3A) of the hologram with the reference speckle-beam formed at the diffuser illumination with the laser beam having TEM₀₀ mode (2A). Altering the intensity distribution of the input beam (1B) and leaving the phase distribution equivalent to that of the mode TEM₀₀ did not much affect the diffracted signal (3B); however, when the reconstruction beam was combined with TEM₀₁ (1C) with its intensity distribution in the plane of the diffuser shown in (2C), the diffracted signal disappears completely (3C). Thus, by changing the complex amplitude distribution from one state to another (both states being orthogonal) we are able to build the holographic data storage module with the solid-state architecture.

It follows from this data that a properly chosen phase-modulation technique of the incoming reconstruction beam will enable design of the holographic memory system with a solid-state addressing scheme. Within the framework of this task, we will study the methods that synthesize optimal phase masks to modulate the incoming reference beam for information multiplexing. This technique of phase pre-encoding of the speckle reference beam can be supplemented with angular deviation (using a beam steering device) of the original beam that illuminated the diffuser. This will also result in de-correlation of the speckle pattern in the recording plane.

Solid-state multiplexing architecture

For the basic design of a solid-state multiplexing system, a low-resolution spatial light modulator (SLM) codes the reference beam before it strikes the speckle encoder. By changing the pattern on the SLM, an entirely new speckle pattern is generated and thus a new hologram can be addressed. During Phase II we will select one of the SLMs based either on direct modulation of the spatial structure/phase of the incoming reference beam, or by using phased array devices, such as ASIL of DigiLens or VLSI of Boulder Nonlinear System Inc. During Phase I, we simulated operation of a solid-state architecture by introducing both amplitude and phase mask information in front of the speckle-encoder (diffuser). The masks had features on the order of 12 microns to simulate the pixel size of spatial light modulators. Experiments were conducted by recording a hologram with the mask in place, reconstructing the hologram, and subsequently moving the mask. Movement of the mask simulated the change that would occur when electronically-shifting the pixels of a spatial light modulator or beam steering over the speckle generator. It was found that the reconstructed intensity decreased as the mask was moved. A typical example of such pre-encoder in action is shown in **Figure 17**, where its spatial shift resulted in a smooth decrease of the diffracted signal intensity. The phase mask had much greater selectivity than the amplitude mask and therefore a phase-only SLM should provide the best results. Identical data have been received at an equivalent spatial decorrelation in any direction in the XY plane, similar to that of physical shift selectivity (see **Figure 11**).

Figure 17. The typical dependence of the diffracted signal intensity upon the spatial shift of the pre-modulator.

Memory capacity

It is important to estimate the information density available through the variety of combinations of 3-D-shift, angular, and wavelength selectivity. The storage capacity of the 3-D hologram with a volume where $V = d^2 \times t$ (where d is the lateral size of the holographic media and t is its thickness) can be calculated as

$$N_V = \frac{4\pi}{3} \frac{V}{\lambda^3}. \quad (11)$$

The expression to determine the total number of multiplexed holograms that can be stored using the shift selectivity scheme is

$$N_\Delta \approx \frac{d^2}{\Delta_\perp^2} \times \frac{t}{\Delta_\parallel}. \quad (12)$$

In addition to that, every recording spot can be multiplexed with the angular speckle selectivity technique. Thus, the total number of holograms that can be recorded using angular-shift selectivity is

$$N_\theta = \frac{2\pi \times (\pi - \theta_{sp})}{(\delta\theta_{sp})^2}, \quad (13)$$

where θ_{sp} is the angular divergence of the speckle beam, and $\delta\theta_{sp}$ is the angular selectivity of the speckle reference wave hologram.

Finally, the correlation function of the speckle pattern is described through the coherence function of the illuminating light. So, changing the wavelength of the recording illumination enables the storage of more "layers" of the holograms and opens an additional mechanism for increasing the capacity of the memory. It was proved experimentally² that a spectral shift of $\delta\lambda \approx 1.5$ nm of the reconstructing wavelength results in total degradation of the diffracted signal. Thus, using a tunable laser with spectral a interval of $\Delta\lambda \gg \delta\lambda$, additional "layers" of information can be stored. The limiting value for information density to be recorded using speckle-encoded reference beam can be found as

$$N_{max} = N_\Delta \times N_\theta \times \left(\frac{\Delta\lambda}{\delta\lambda} \right). \quad (14)$$

This leads to the data storage capacity for $1 \times 1 \times 1$ cm³ recording media using speckle reference beam with the following characteristics: $\Delta_\perp \approx 3$ μ m; $\Delta_\parallel \approx 30$ μ m; $\theta_{sp} \approx 15^\circ$; $\delta\theta_{sp} \approx 3 \times 10^{-4}$; and $\delta\Delta/\delta\lambda \approx 100$: $N_{max} \approx 10^{18}$ holograms. If every hologram is a page of information with 1 Mbit, then total capacity can be estimated as 10^{23} bits; however, taking into account the limited range of the recording media refraction index modulation, the most optimal combination of the selectivity will be chosen which optimizes the number of holograms that can be stored. This selection will be focused towards development of a solid-state memory system. The dynamic range for the recording media refraction index modulation is limited and is normally within the frame of $\Delta n \leq 1.3 \times 10^{-2}$ for photopolymer materials and $\Delta n \leq 10^{-4}$ for photorefractive crystals. Therefore, the proper and most efficient choice of the selectivity mechanism to be used is particularly important, as it determines the storage density and capacity of the memory unit.

With optimized CMOS detectors, the average diffraction efficiency can ultimately be around 10^{-8} which corresponds to a refraction index modulation on the level of $\Delta n \leq 1.6 \times 10^{-8}$. With this value of diffraction efficiency for each individual hologram, about 10^5 holograms can be multiplexed in a PRC and 10^6 in photopolymer (100 Gbit and 1 Tbit, respectively) at one location. To realize such a high storage capacity, a thorough study of multiplexing is of primary importance.

Another limiting factor for the holographic memory system is the noise, which, to a large extent, is due to the light scattering by the recording media and residual cross-talk at hologram reconstruction. For 3-D speckle shift holograms, the SNR ratio can be estimated as

$$SNR_{\Delta_\perp} = \frac{I_{diff}(m)}{I_{diff}(n) \sum_{n \neq m}^N \left| \frac{2 \langle \varepsilon_\perp \rangle}{n \times \Delta_\perp} J_{1n} \left(\frac{n \times \Delta_\perp}{\langle \varepsilon_\perp \rangle} \right) \right|^2 + I_{ns}}, \quad (15)$$

where I_{ns} is the noise due to light scattering by the recording media itself. This does not take into account the self-amplified noise component, generated at multiple hologram exposure. Therefore, the study of the kinetics of the holographic recording at multiple exposure is of importance.

The SNR was calculated as a function of lateral shift Δ_L for two cases when the aperture that bounds the illuminated area of the diffuser has rectangular or circular function geometry and Gaussian form (see Figure 18). It is seen from the calculations that the sharp form of the aperture leads to oscillating behavior of the $SNR(\Delta_L)$ while the Gaussian illumination results in a smooth increase of SNR. The reason for this behavior of the $SNR(\Delta_L)$ in the first case is because the correlation function was selected in a simple form $J_1(x)/x$; however, in both cases, the limiting value of SNR is close to 100 for the simulated conditions and geometry of the hologram recording.

Very similar characteristics of SNR can be found for both angular and wavelength speckle beam multiplexing. Since all types of the noise (resulting from cross-talk and intrinsic features of the recording media) have an additive (accumulative) character, the combination of several techniques of selectivity (shifting, angular and spectral) should not greatly affect the limiting value of the SNR.

Figure 18. Calculated signal-to-noise ratio as a function of spatial shift for cases of Gaussian and circular aperture functions.

The average level of SNR for each of the holograms reconstructed in these experiments was ≤ 45 . It was measured as the ratio between the Fourier-filtered DC component of the diffracted beam and the collected scattered light that propagates in the same direction. At fixed experimental conditions, such as recording beams ratio, exposure level, form of the aperture in diffuser plane, etc., the value of the SNR depends upon the ratio between the introduced shift $\Delta_{L,II}$ and the magnitude of the correlation radius $\langle \sigma_{L,II} \rangle$ in the corresponding direction.

The noise level is an important factor in holographic memory systems with multiple recording. The level of noise (as well as the dynamic diapason of the recording media refraction index modulation) on one hand will determine the ultimate number of the recorded data-pages, while on the other, the level of the memory system's security. For SERW volume holograms, as was shown previously, the amplitude of the reconstructed signal is proportional to the mutual intensity MI function, while the magnitude of the last one is determined by the aperture function of the diffuser.

Once the speckle selectivity of the volume hologram is considered, the diffracted (reconstructed) signal intensity is proportional to the Fourier transform of the aperture function, which is equivalent to Eqn. (7). It follows from this Equation that the level of the "mutual influence" of recorded holograms is determined by the spatial Fourier spectra of the aperture function. Therefore, to minimize this effect, it is important to choose the function with a minimal level of the intensity at its "wings". Thus, in order to determine the impact of the neighboring holograms on the signal beam, it is sufficient to examine the spatial structure of the function $\mu(\alpha, \beta)$ upon the magnitude of the shift in the directions α and β .

Let's determine the aperture function within the class of sub- and super-Gaussian functions that are easy to assemble experimentally. We assume in this analysis, that the aperture function is symmetric and can be described as:

$$P(\zeta, \eta) = \exp \left[- \left(4 \frac{\zeta^2 + \eta^2}{a^2} \right)^{n/2} \right] \times \varphi(\zeta) \times \varphi(\eta) \quad (16)$$

$$\varphi(\rho) = \begin{cases} 1 & \text{if } |\rho| \leq \rho_0 \\ 0 & \text{if } |\rho| > \rho_0 \end{cases}$$

It is evident that at $n = 0$, the aperture function is described by the product of the standard Gaussian distribution multiplied by the cut-off function $\varphi(\rho)$. Using the cut-off function in this case is justified by the fact that the laser beam has limited aperture or the recording medium's lateral dimensions are limited.

Let's consider first the square aperture geometry, which allows splitting the variables in Eqn. (16) and reducing the problem to the one-dimensional level. Figure 19 illustrates several configurations of the aperture function and corresponding levels of the reconstructed signal beam. For better perception, the fixed levels of the signal beam (10^{-6} , 10^{-4} , 10^{-2}) are normalized on the corresponding maximal value of the intensity.

The aperture function clearly has a sharp edge, and therefore its angular spectrum is wide, making the cross-talk level high. The aperture $a \geq 2$ and the value of n in the interval between 2 to 4 reduces the cross-talk level.

Figure 19. Distribution of the laser beam intensity in the plane of encoder.

Design compact prototype system

Based on the results of the previous tasks, we will design a compact prototype system. The prototype system will consist of three elements: a data recorder, a memory cell, and a data reader. A preliminary design for the system is shown in Figure 20. The data recorder consists of a high power laser (possibly pulse laser) for rapid data recording, high resolution SLM for data encoding, multiplexing elements

(shown here with a phase SLM, but it could also be a beam steering or similar device), and a monitoring detector (or detector array) to determine when the proper exposure is achieved. The Memory Cell consists of the holographic volume element, the speckle generator and relay optics. The Reader consists of a low power laser, a multiplexing element and a detector array. The Reader can be produced much cheaper than the Recording Unit due to the lower power laser and absence of a high resolution, high speed SLM for data encoding. Note that the Recorder may also function as a Reader.

Figure 20. Preliminary design of Recorder, Reader and Memory Cell for Phase II prototype memory system.

We also predict that modifications of the compact memory unit that can incorporate the laser, encoder and holographic medium, can operate as an autonomous hard disc. The principal configuration of the disc-format memory module is shown in **Figure 21**. Here the reference beam, after being encoded with random mask, interferes with signal beam and in this medium is the holographic data page is memorized. After each exposure, the relative position of the medium and random mask is mismatched by the distance Δ_1 by disc rotation and data multiplexing is achieved. The first virtual "layer" L_1 is stored once the "surface" of the disc is entirely exposed. Now, as the thickness T of recording material is larger than longitudinal shift selectivity ($\Delta_{||}$), changing the relative position between the recording head and disc on $\Delta_{||}$ allows us to form the next "virtual layer" L_2 . Note that both layers with multiplexed data occupy the entire volume of the recording medium.

Figure 21. Principal scheme of the multilayer SERW holographic memory module.

In the architecture of the memory module with disc configuration, the multiplexing scheme is identical to the one presented in Figure 1a. The construction of the disc may include the module of laser and random mask (L&RM), and detector that are incorporated in one housing (see Figure 22). The operational principle of such a memory module will be as follows: Once the multiplexing is accomplished and the disc is fully exposed, it will be placed in the housing. The housing will be assembled with the L&RM that forms the SERW and will be totally identical to the recording medium. Turning the disc and shifting synchronously the L&RM and detector will allow us to recall the requested data page. Presented below are the preliminary designs of the memory module, which is similar to the CD-ROM although it exceeds its storage capacity by at least 10^3 times.

Figure 22. Rigged disc design for ultra-high density holographic memory module.

Preliminary design estimates

LASER SELECTION

In order to develop a compact, robust system, it is necessary to use a solid-state laser system. Laser diodes are ideal in terms of compact size and robustness; however, at present, they are only available at wavelengths longer than 600nm where polymer and photorefractive materials have low efficiency. In addition, the wavelength of each diode can vary by several nanometers between each diode. The high spectral selectivity of the speckle multiplexing technique would prohibit the use of such large changes in wavelength that could occur between the Reader and Recorder. Therefore, at this time, laser diodes are not the best choice for the prototype system; however, this technology continues to evolve and could be a suitable choice in the future. Part of our design task will be to re-evaluate progress in laser diode technology that has occurred since the writing of this proposal. On the other hand, once the memory module in the "hard-disc" configuration is developed, the diode lasers should be the best candidates to be used here.

For the first prototype system we anticipate using a solid-state, frequency doubled, YAG laser as the writing and reading source. They are available as compact high power modules. Wavelength stability is excellent and coherence length can exceed 1 meter (path matching is not necessary). Development of a solid-state, frequency doubled YAG laser remains an active area of research by many companies and therefore we expect the available power to increase and prices to continue dropping in the future.

READ-OUT RATE

The laser power required to achieve a specific read-out rate can be calculated according to

$$P = \frac{\Delta E \cdot N_{read}}{\eta_1}, \quad (17)$$

where ΔE is the energy exposure necessary for a single exposure of the detector, N_{read} is the reading data rate, and η_1 is the diffraction efficiency of a single hologram. A plot of the required laser power vs. data rate is shown in **Figure 23**. In this figure we assumed a detector sensitivity of 1 nJ/frame (typical number for a CCD) and a diffraction efficiency of 10^{-5} per hologram (conservative estimate for 10,000 holograms). For 1 Gbit/second read-out, a 100 mW laser is required. Diode pumped, frequency doubled YAG lasers are commercially available in this power range as compact solid-state devices. Note that for reading at more modest rates (full video) a 1 mW laser can be used.

Figure 23. Required laser power as a function of required data rate for recording (solid line) and reading (dashed line).

RECORDING RATE

The power required for the writing of holograms can be estimated using

$$P = \frac{\Delta F \cdot A \cdot N}{1 - \kappa}, \quad (18)$$

where ΔF is the fluence required per hologram exposure, A is the area of the recording beam at the sample, N is the record rate in holograms per second, and κ is the total optical loss of the system. **Figure 23** plots the calculated laser power as a function of the data rate based on a material sensitivity per exposure of 2.5 mJ/cm² (Polaroid material),²⁷ an aperture of 1 cm, and optical losses of 30%. A recording rate of 1Gbit/second requires a laser power of 3 Watts, which is possible with today's technology (laser cost ~ \$30k). The laser we anticipate using (100 mW) will be capable of sustained data rates of ~ 30 Mbit/second, which exceeds our Phase II design goal of 7 Mbit/second (full video frame rates). At that rate, the memory can be filled in 23 minutes.

RESEARCH RESULTS

The following results were achieved during Phase I of this project:

1. We performed analytical and numerical modeling of the expected 3-D shift selectivity for hologram recorded with **SERW**. It follows from these calculations, that the use of speckle wave multiplexing had significant advantages over established forms of multiplexing used for holographic data storage by increasing the storage capacity by over 3 orders of magnitude.
2. Performed an analysis of the possible methods of alteration of the orthogonal states in the reference beam, leading to the modification of the spatial amplitude-phase composition in **SERW**.
3. Constructed a fully automated, optical memory system breadboard with a LiNbO₃ crystal and thick photopolymer film as the recording medium.
4. Demonstrated the storage and recall of the data pages in both solid-state and shift-and-read configurations with the SUPERB architecture with complex images in the memory. Each data page can contain significant amounts of information (~ MB), which results in enormous data transfer rates since an entire data page is reconstructed simultaneously. We performed recall of 103 kbits data-page with 10 msec frame rate using a CMOS VV5404 detector.
5. Calculated an estimated storage capacity of ~ 10⁹ holograms for a 1 cm³. This corresponds to an estimated storage capacity of over 1000 Terabits within the small volume of material.
6. Demonstrated a new, modified multiplexing scheme that combines speckle waves with phase code multiplexing to create a no-moving-parts system. This modified scheme has the potential to offer extremely robust operation suitable for high vibration/shock environments (compact mobile modules, such as the navigation information gathering systems for air or spaceflight, unmanned vehicle, etc.)

POTENTIAL APPLICATIONS

We came up with two concepts of the high-density holographic memory based on the results obtained during this Phase I project:

- The solid-state configuration (SSC) read-write memory module with limited capacity and high throughput.
- The holographic memory for a removable, write-once, read-many (WORM) module that can be expanded into a "play and exchange" magazine with a single disc tray for a conventional playback of a multiple discs. This approach can lead to development of very high-capacity memory modules for permanent data storage system (silo).

Some of the possible applications for this technology are shown in Figure 24. In the case of SSC, a high-speed writing device is used to record the data into the memory cartridge (size ~ 75 cc). The cartridge can then be placed in a variety of applications that requires large amounts of stored data and high transfer rates, including local networks, or small and very local operational systems. Such a SSC module can be used also for the navigation system or the system that requires the identification and comparison of the data taken at different times or at different space domains. The SSC module can also serve as an intermediate data storage platform, for instance, when the communication link is time-limited or cyclical. An important advantage of the proposed memory concept is the secured access to the stored data. Inherent immunity to the "entrance" encoder duplication makes this memory configuration highly protected against non-authorized entry. Alternatively, a very high-capacity silo can be built using the WORM strategy. Such a memory system will collect and store for a long time (in principle, infinitely) the information that does not require very high access time, but requires fast exchange.

Figure 24. Applications for proposed memory system.

Product Feasibility

The commercial product anticipated from this project is a compact, high capacity, high transfer rate, digital data storage module. During Phase I we demonstrated the ability to store information within a photorefractive crystal and thick layer photopolymer film using random encoded (speckle) reference wave multiplexing at an equivalent surface density that is six orders of magnitude greater than existing storage media. The initial prototype system will aim for a storage density that is 10 to 100 times greater than existing systems. We anticipate packaging the device in a 0.25 cu. ft. form factor. Such a prototype will demonstrate the potential of the technology and should be sufficient to solidify the partnership with commercial or venture companies such as Siros Technologies, Inc. Once the prototype is demonstrated, we estimate that an investment on the order of \$3 to \$5 million will be necessary to reduce the device to a typical 5 1/4" form factor and establish an industry-compatible I/O interface.

Two categories of technical innovations are important in the long-term development of a commercial, high-density, holographic memory system: storage media and electro-optic hardware. The recording media characteristics define the ultimate capacity of the system and set the power and wavelength requirements for the laser. Multimillion dollar efforts are currently underway to improve holographic

media through the PRISM consortium (funded by DARPA). Polaroid recently established a spin-off company by the name of *Aprilis* that will supply high-resolution holographic material that was tested as an efficient data storage medium.

Significant progress has been achieved during last several years with development of SLM and detector technology. For example, DigiLens™ ASIL devices operates with high spatial resolution and switching times as short as 10 μm and power consumption at about 30 mW. In the same way, the combination of two linear elements 1 x 4096 beam steering arrays with a pixel size of 1 μm from BNS will allow us to generate a beam array with 256 x 256 spots. The diffraction efficiency of both elements is about 80%. As for detectors, the advance with low power consumption CMOS devices makes it possible to get resolution at the receiver end down to 7 μm in the production line and about 3 μm in development. Thus, the progress in these two technologies satisfies the requirements for practical memory module design and development.

Market Feasibility and Competition

Rapid advances in society's abilities to sense, collect, transmit and process digital data are leading to almost explosive data storage system growth. With an estimated 3.2 Petabytes of information flowing through the Internet each month, multi-terabyte caching are becoming commonplace, and as more commerce shifts towards electronic forms, reliability and achievability will become even more critical.²⁶

A robust, high density, 3-D optical storage device would find widespread application in both the Federal Government and in the commercial sector. Applications within the government include archival storage of intelligence and statistical information in ground-based systems, storage of detailed terrain mapping for aircraft, missile, and spacecraft systems, and storage of operating systems and application software for a wide range of computer applications. The most promising area for commercial success is in the area of computer information storage. Almost every business employs computers with mass storage. With more powerful computers, growing networks, and the increased processing of multimedia files, the demand for mass storage is growing exponentially. The entertainment industry alone fuels a tremendous need for increased mass storage for such applications as virtual reality and digital motion pictures. Application of the proposed configuration of the ultra-high density memory module with a capacity in the range of 10^{15} will enable them to assemble a disc-like film library with more than 10^3 full-color (RGB) movies each 2.5 hours long. Image data storage systems like this are of primary interest for hospitals, clinics and doctors' offices, where imaging systems have been already installed, and many more are considering this technology as they move toward an electronic patient record²⁷.

Forecasts made by the National Storage Industry Consortium predict that during next few years, the demand for new storage devices will exceed 350,000 Terabytes and the installed base will be over 1,000,000 Terabytes (1,000 Petabytes). Effective utilization of information technologies in the 21st century will require storage technologies with capabilities that exceed the potential of current technologies. The 3-D memory developed in this program would give these industries a tremendous increase in storage capacity, and transfer rates.

Revenues in the commercial mass storage industry currently total over \$40 billion annually. We estimate an initial market penetration for holographic data storage (after 3-4 years of development) of 0.1%, resulting in a \$40 million annual market. After 5 - 10 years, market penetration could reach 10%, resulting in a \$4 billion dollar market. Because of the shared nature of the development, several patents will apply in addition to our own and thus a negotiated royalty in the range of 0.5% - 1.0% is expected. The resulting royalty stream for MetroLaser is approximately \$400k annually after 3-4 years and \$40 million annually after 5 to 10 years. The expected U.S. Government market is roughly 10% of the commercial sector. Therefore, the overall market size and potential return strongly justifies additional research and development activity. The above discussed market volume is based only on the proposed

module's application in storage systems and does not include its possible harnessing in the film industry, which can open significant market potential for the proposed memory system.

Development of a "next generation" storage device is an on-going area of investment for many commercial companies including IBM, Lucent Technologies, NEC Siro's Technologies, Inc., and others. While commercial products are not yet available, considerable speculation has been published regarding the emergence of this technology.^{28,29}

REFERENCES

- ¹ M. Keshner, "Status of optical storage in Japan, in WTEC panel report on the future of data storage technologies", June 1999 (National Science Foundation International technology Research Institute).
- ² Sub-terabit optical memory project: <http://www.oitda.or.jp>
- ³ NSIC/OIDA Optical disk storage roadmap, National storage industry consortium, pp. 3-15, (1997).
- ⁴ C. Wilde, *Easier Archiving*, Information Week, August 23, 1999.
- ⁵ A.A. Jamberdino, "Storage and retrieval: the next generation" Report at the SPIE-3208 Conference, "Advanced optical data storage: Materials, systems, and interfaces to computers", July 1999.
- ⁶ P.J. Van Heerden, "Theory of optical information storage in solids", *Appl. Opt.* 2, 156 (1963).
- ⁷ F.H. Mok, "Angle-multiplexed storage of 5000 holograms in lithium niobate", *Opt. Lett.* 18, 915 (1993).
- ⁸ S. Tao, D. Selvan, J. Midwinter, "Spatio-angular multiplexed storage of 750 holograms in an Fe:LiNbO₃ crystal", *Opt. Lett.* 18, 912 (1993).
- ⁹ J. Rosen, "Dynamic phase-encoding storage of 64 images in a BaTiO₃ photorefractive crystal", *Opt. Lett.* 18, 744 (1993).
- ¹⁰ G.A. Rakuljic, V. Leyva, A. Yariv, "Optical data storage by using orthogonal wavelength-multiplexed volume holograms" *Opt. Lett.* 17, 1471 (1992).
- ¹¹ A. Darskii and V. Markov, "Some properties of 3D holograms with a reference speckle-wave and their application to information storage", SPIE Proc. V.1600, pp. 318-332, (1992).
- ¹² V. Markov, Yu. Denisyuk, and R. Amezcua, "3-D Speckle-shift hologram and its storage capacity", *Optical Memory and Neural Networks* v. 6, No 2. pp. 91-98, (1997).
- ¹³ D. Psaltis, M. Leven, A. Pu, et al., "Holographic storage using shift multiplexing", *Opt. Lett.* 20, 782 (1995).
- ¹⁴ J. Rosen, "Multilayer optical recording", SPIE Proc. 2514, 14 (1995).
- ¹⁵ S. Chinn and E. Swanson, "Multilayer optical storage by low-coherence reflectometry", *Opt. Lett.* 21, 899 (1996).
- ¹⁶ P.A. Mitkas, L.J. Irakliotis, and G. Betzos, "Optical Processing Paradigm for Electronic Computers", *IEEE Computer*, 31, 2, pp. 45-51, (1998).
- ¹⁷ N.V. Kukhtarev, V.B. Markov, and S.G. Odulov, "Transient energy transfer during hologram formation in LiNbO₃ in external electric field", *Optics Communications*, v.23, pp. 338-343 (1977).
- ¹⁸ E. Jakeman, "Enhanced backscattering through a deep random phase screen", *J. Opt. Soc. Am. A* 5, pp. 1638-1648, (1988).
- ¹⁹ V. Sidorovich, "Diffraction efficiency of three-dimensional phase holograms", *Sov. Phys. Tech. Phys.*, v. 21, pp. 742-745, (1976).

-
- ²⁰ B. Zel'dovich, V. Shkunov, and T. Yakovleva, "Holograms of speckle field", *Soviet Physics - Uspekhi*, v.29 pp. 678-702, (1986).
- ²¹ V. Markov, M. Soskin, A. Khizniyak, and V. Shishkov, "Transformation of the structure of coherent light beams by volume phase holograms in LiNbO₃", *Soviet Techn. Phys. Lett.*, v.4, pp.304-6. (1978).
- ²² A. Darskii and V. Markov, "Shift selectivity of the holograms with speckle reference wave", *Opt. Spectrosc* v. 65, pp.392-394, 1988
- ²³ J. W. Goodman, "Statistical properties of laser speckle pattern" in book "Laser speckle and related phenomena" Ed. J. Dainty, Springer-Verlag, (1984).
- ²⁴ W. Liu, A. Abidi, and D. Psaltis, "Rewritable holographic memory", *SPIE Proc.*, Vol. 3864, pp.94-96, (1999).
- ²⁵ V.B. Markov "Coherent field orthogonalization with speckle-wave volume hologram" *SPIE Proc.*, Vol. 3486, (1998).
- ²⁶ See, for example, at: <http://www.inktomi.com/about/overview.html>
- ²⁷ P. Waagemann and S. Cisco "The Handbook of Optical Memory Systems", Medical Records Institute, 516 (1994).
- ²⁸ WIRED Magazine "Holographic Storage", November 1997.
- ²⁹ Datamation "Six Hot Technologies for the 21st Century", August 1996.