High Density Holographic Memory

Presented to
Int’l Symposium on Optical Memory

Presented by
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Objectives and Performance Specifications

- **Objectives**:
  - Develop innovative memory technologies to enable large-capacity, high-speed, read/rewrite of image and digital data in a space environment
  - **Demonstrate key capabilities**:
    - Ultra High data/image storage capability (1TB)
    - High-speed random access data transfer (1GB/s)
    - Radiation-resistance

- **Performance Specifications**
  - A compact holographic data storage with 10 GB non-volatile random access memory per cube
  - Up to 10 x 10 cubic memory can be stacked into an ordinary memory board size to achieve a storage capacity of 1TB
  - Read/rewrite, rad hard, high transfer rate
Holographic Memory Light Budget

**GOAL:** Video-rate recording with storage capacity of 10,000 pages of 1,000x1,000 gray-scale images.

List of materials available for this application

<table>
<thead>
<tr>
<th>thickness</th>
<th>LiNbO$_3$ Fe √</th>
<th>LiNbO$_3$ Fe, Mn √</th>
<th>LiNbO$_3$ Cr, Cu √</th>
<th>Green Polymer *</th>
<th>Red Polymer *</th>
<th>PMMA Polymer √</th>
</tr>
</thead>
<tbody>
<tr>
<td>shrinkage</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes (3%)</td>
<td>yes (3%)</td>
<td>yes (2%)</td>
</tr>
<tr>
<td>wavelength</td>
<td>488nm</td>
<td>red+UV</td>
<td>red+blue</td>
<td>532nm</td>
<td>630-670nm</td>
<td>488nm</td>
</tr>
<tr>
<td>need fixing</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>dynamic range</td>
<td>large</td>
<td>large</td>
<td>large**</td>
<td>modest</td>
<td>modest</td>
<td>modest</td>
</tr>
<tr>
<td>wiring speed rewriteable</td>
<td>slow</td>
<td>very slow</td>
<td>slow**</td>
<td>very fast</td>
<td>fast</td>
<td>fast</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

* Thin materials only. Large-scale storage might be problematic with non-mechanical scanners.

** Projected.
For non-volatile storage of 10,000 holograms, the target diffraction efficiencies are,

\[ \eta_h = \left( \frac{M/\#}{M} \right)^2 \]

<table>
<thead>
<tr>
<th></th>
<th>LiNbO$_3$ Fe</th>
<th>LiNbO$_3$ Fe, Mn</th>
<th>LiNbO$_3$ Cr, Cu</th>
<th>Green Polymer</th>
<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M/#)</td>
<td>10*</td>
<td>10</td>
<td>30**</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(\eta_h)</td>
<td>2.5x10^{-7}</td>
<td>10^{-6}</td>
<td>10^{-5}**</td>
<td>3.6x10^{-7}</td>
<td>2.5x10^{-7}</td>
<td>2.5x10^{-7}</td>
</tr>
</tbody>
</table>

* The \(M/\#\) drops approximately by a factor of 2 after thermal fixing in LiNbO$_3$:Fe.
** Projected value.
## Light Budget Estimate

1. **Photon-limited readout:**

   \[ N_e = \eta_{tr} \eta_q \frac{\eta_h \eta_{im} P_{in}}{hv} \frac{1}{r_{ON} N_p t_{int}} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>number of signal electrons</td>
<td>(~25,000^*)</td>
</tr>
<tr>
<td>(\eta_{tr})</td>
<td>electron transfer efficiency</td>
<td>0.9**</td>
</tr>
<tr>
<td>(\eta_q)</td>
<td>quantum efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>(\eta_h)</td>
<td>hologram diffraction efficiency</td>
<td>From above</td>
</tr>
<tr>
<td>(\eta_{im})</td>
<td>efficiency of readout optics</td>
<td>0.9</td>
</tr>
<tr>
<td>(P_{in})</td>
<td>readout power</td>
<td>?</td>
</tr>
<tr>
<td>hv</td>
<td>power per electron</td>
<td>4.073x10^{-19} J</td>
</tr>
<tr>
<td>(r_{ON} N_p)</td>
<td>number of ON pixels</td>
<td>0.5x10^6 ***</td>
</tr>
<tr>
<td>(t_{int})</td>
<td>integration time</td>
<td>1 sec.</td>
</tr>
</tbody>
</table>

* For binary data, 100 photoelectrons at a pixel are needed for optimal hard thresholding, considering electronic, optical, and holographic noise.

** Worst-case transfer efficiency from CCD to external electronics.

*** Exact number for binary random-bit patterns.
### Readout powers for 1-second integration time

* Projected value

<table>
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<tr>
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<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pᵢₙ (mw)</td>
<td>28</td>
<td>7</td>
<td>0.07*</td>
<td>19</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

### Recording speed

1. recording speed for 10,000 holograms (target diffraction efficiency is 10⁻⁷).

<table>
<thead>
<tr>
<th></th>
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<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing energy</td>
<td>3</td>
<td>100*</td>
<td>1**</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>mJ/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Writing</td>
<td>100</td>
<td>333*</td>
<td>33**</td>
<td>3.3</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mw/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For recording at He-Ne line. Data for blue recording is not available at the moment.

** Projected value.
System Schematic of an Advanced CHDS Architecture

Unique Advantages

- **Very compact**
  - Cubic package with the size of a cigarette box

- **Massive data storage**
  - store up to $10^4$ pages of hologram with 10 Gbytes capacity

- **High-speed**
  - current throughput 200 Mbytes/sec achieved with using a LC Beam Steering Device. Could be 10x faster if FLC is used

- **Device/components maturity**
  - Use two single diode lasers that are commercially available at low cost
  - Beam Steering Device is a emerging technology. JPL is actively engaged with BNS in developing the next generation high-speed version
Liquid crystal phased array beam steering device

- Beam steering based on optical phase modulation

Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-2\(\pi\) ramp with a period \(d\) which determines the deflection angle \(\theta\)
Liquid crystal phased array beam steering device

- Diffraction efficiency:

\[ \eta = \left( \frac{\sin(\pi/n)}{\pi/n} \right)^2 \]

\( n \): number of steps in the phase profile
\( \text{e.g., } \eta \sim 81\% \text{ for } n=4, \eta \sim 95\% \text{ for } n=8 \)

- Deflection angle:

\[ \theta = \sin^{-1}(\lambda/d) \]

\( \text{for the first order diffracted beam} \)

- Number of resolvable angles:

\[ M = 2m / n + 1 \]

\( m \): pixel number in a subarray
\( n \): minimum phase steps used

\( \text{e.g., } M = 129 \text{ for } m=512, n=8 \text{ with a } 1\times4096 \text{ beam steering device} \)
Photograph of a Liquid Crystal Beam Steering Device

Surface phase-modulation profile of a beam steering device
LabVIEW Based Controller for Beam Steering

- Use LabVIEW to calculate the theoretically correct beam steering profile (i.e. sawtooth wave).
- Optimize the diffractive efficiency and suppress the spurious high orders
- A hardware-in-the-loop routine has been developed to customize the driving voltage for each and every beam deflection angle
- A nonlinear waveform of the driving voltage profile is obtained for good performance
Sawtooth Profile

- The resulting profile (using an input value or N* of 57):

*The input value is proportional to the number of gratings on the device.*
Tangent Profile

- For optimal results, parameters must be chosen such that the entire range of 0-256 is used with 0 and 256 occurring with a consistent period.
- The selected parameters are unique for each angle.
Resulting Diffraction Patterns

- The spurious higher orders of diffraction are nearly eliminated by using the nonlinear voltage driving waveform to the liquid crystal B SSLM.
Liquid crystal phased array beam steering device

- Cascaded beam steering architecture:

Input beam

$M_1$-angle 1-D beam steerer

$M_2$-angle 1-D beam steerer

$M_1 \times M_2$ 1-D or 2-D output beam directions

A total resolvable angels of more than 10,000 can be easily achieved.
Benefits of using LC SLM beam steering devices:

- No mechanical moving parts
- Randomly accessible beam steering
- Low voltage / power consumption
- Large aperture operation
- No need for bulky frequency-compensation optics as in AO based devices
Performance Characteristics of LC Beam Steering Device

- Number of pixels: 4096 Reflective
- VLSI backplane in ceramic PGA carrier
- Array size: 7.4 x 7.4 mm
- Pixel size: 1μm wide by 7.4mm high Pixel pitch: 1.8 μm
- Response time:
  - 200 frames/sec with Nematic Twist Liquid Crystal
  - 2000 frames/sec with Ferroelectric electric Crystal (under development)
Photograph of a JPL compact holographic memory breadboard developed under the sponsorship of NASA ESTO

Dr. Tien-Hsin Chao
Advanced Holographic Memory Task
Experimental results showing retrieved holographic images of a Toutatis Asteroid
Summary and Future Work

• We have developed (with BNS Inc.) a new liquid crystal beam steering device for high-speed, random access beam steering for angularly multiplexed hologram recording
• We have developed a compact CHDS breadboard and demonstrated grayscale holographic data storage/retrieval
• We will continue to integrated a 2-D angularly multiplexing scheme to achieve > 10,000 page of holograms store per PR cube
• We will also started radiation tests of holographic data stored in a LiNbO$_3$ PR crystal
• We will also investigated non-volatile hologram storage using 2-wavelength PR crystal