Compact Holographic Memory Using Electro-optic Beam Steering Devices

Presented to Non-Volatile Memory Technology

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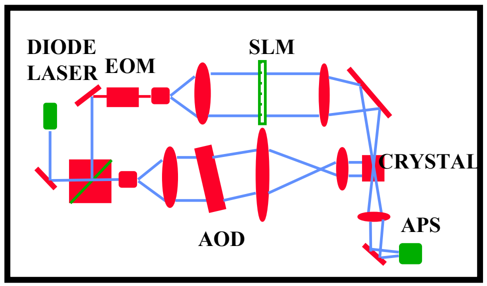
Unique Advantages of Holographic Memory

Advantages of Holographic Memory

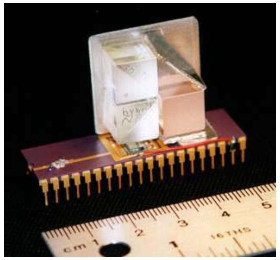
- Large-capacity, high-speed, read/write of image and digital data in a space environment
- Very large capacity/density
  - **V/λ^3, or 1Tb/ 1 cm^3 cube**
- Extremely fast recording / data transferring
  - **Parallel (pages) vs sequential (bits)**
- Exceptional reliability for space environment
  - **No moving parts**
  - **Fault and local-damage tolerance**
  - **Radiation Resistance**

==> Not simultaneously available with electronic and magnetic storage technologies !

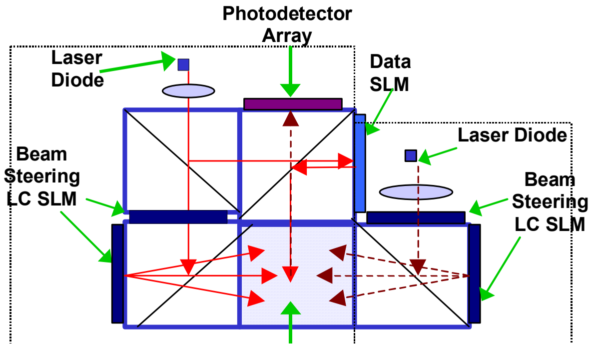
Comparison of Holographic memory Technologies



Previous JPL holographic memory using Acousto-optic scanner



Cubic Holographic memory using VECSEL array (Caltech approach)



Current JPL innovative approach using BS scanning devices

Pros

- AO device mature
- High-speed
- Medium density (x1 AO)

Cons

- Bulky (AO device requires lens set for beam forming)
- High-density storage requires 2 cascaded AO, very difficult for miniaturization

Pros

- Very compact using VECSEL array for multiplexing
- High-speed
- Medium density

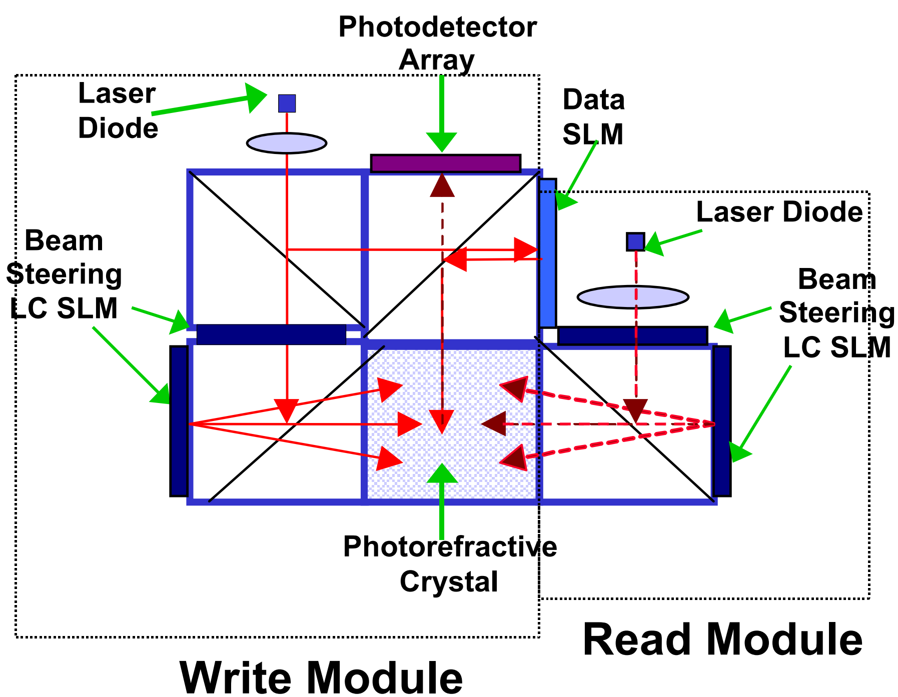
Cons

- High-density storage requires high-density VECSEL array
  - 10 x 10 array available to date
  - with only 4 mW power for each laser source (1/20 of needed power

Pros

- Very compact using BS device
- High-speed
- High density achievable with using 2 cascaded BS devices
- Use 2 single diode laser (commercially available)
- BS device is an emerging technology with a road map for performance optimization

System Schematic of Advanced Holographic memory Architecture



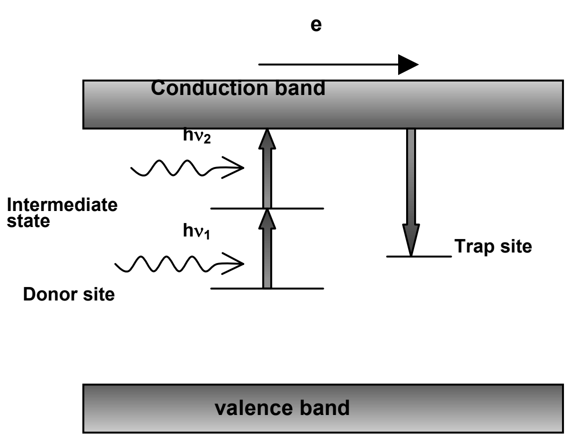
Unique Advantages

- **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

Nonvolatile Two-photon (or Gated) Recording

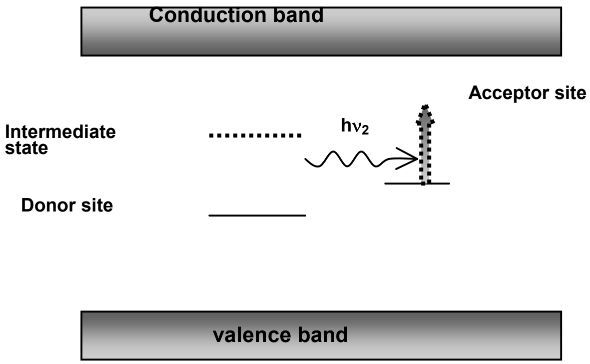
Recording

- First photon (e.g., uv, green) excites an electron to an intermediate state
- Second photon (e.g., red, near-IR) further promotes it to the conduction band
- The electron then migrates & gets trapped to record the interference pattern



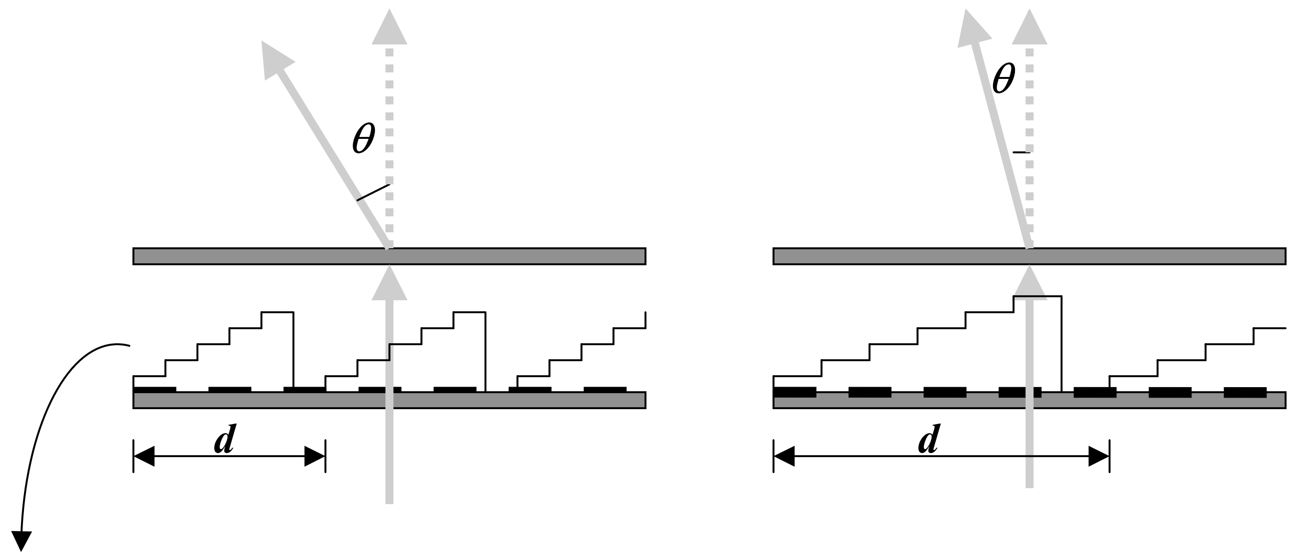
Readout

- Readout by a single photon (e.g., red) ==> insufficient energy to promote electron to C.B., no photoexcitation
- No erasure of data
- To erase: use both photons



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-2π ramp w/ a period *d* which determines the deflection angle θ

Liquid crystal phased array Beam Steering Device

- **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)

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**

e.g., η ~ 81% **for *n* =4,** η ~95% **for *n* =8**

- **Deflection angle:**

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

for the first order diffracted beam

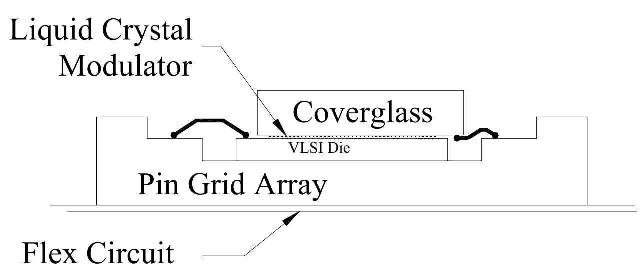
- **Number of resolvable angles:**

$$M = 2m/n + 1$$

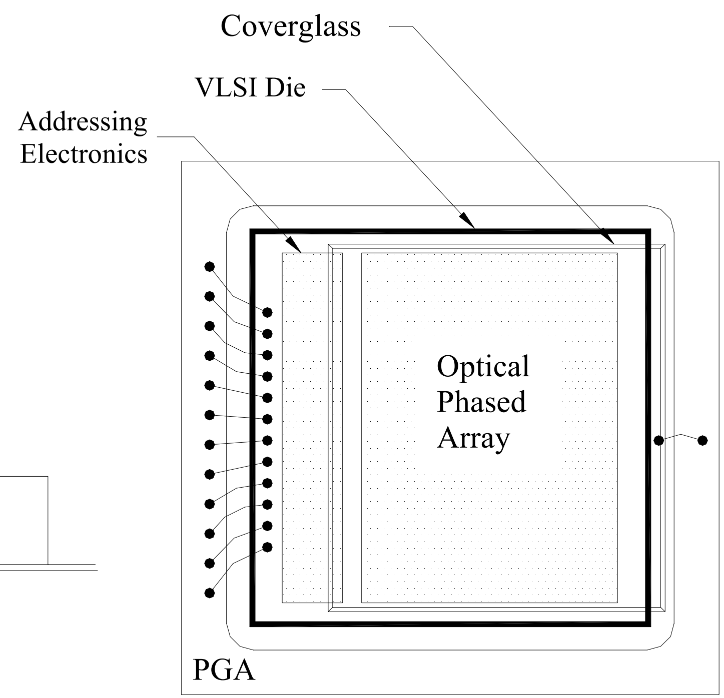
***m*:pixel number in a subarray**
***n*: minimum phase steps used**

e.g., M **= 129 for *m*=512, *n* =8 with a 1x4096 beam steering device**

Layout of Optical Phase Array Optical Head

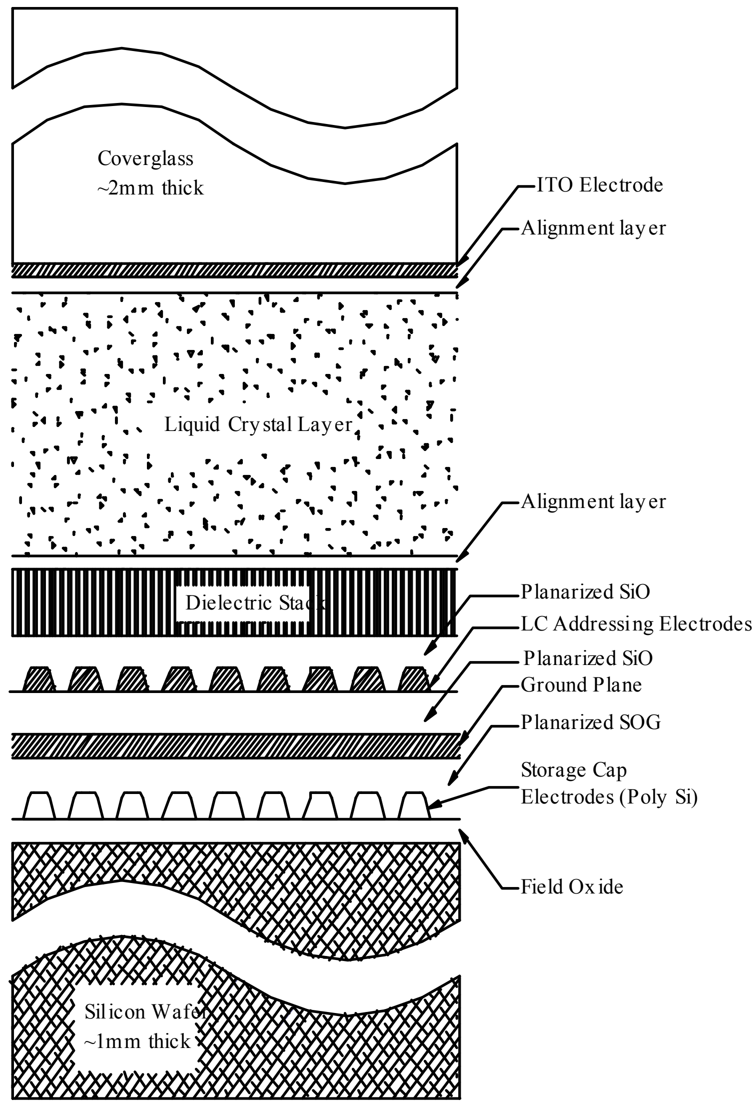


Side View

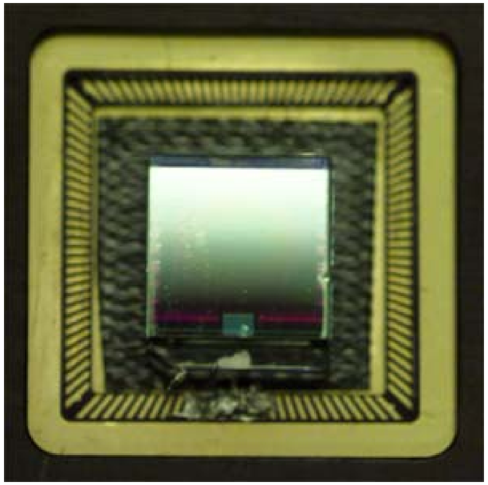


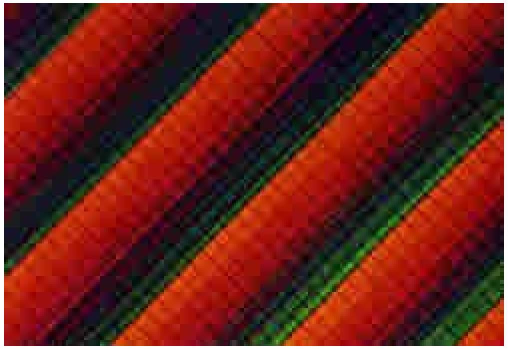
Plan View

Cross Section of OPA Head



Photograph of a Liquid Crystal Beam Steering Device





Surface phase-modulation profile of a beam steering device

Liquid crystal phased array beam steering device - Performance specifications

- **Diffraction efficiency:**

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

***n*: number of steps in the phase profile**

***e.g.*, η ~ 81% for *n* =4, η ~95% for *n* =8**

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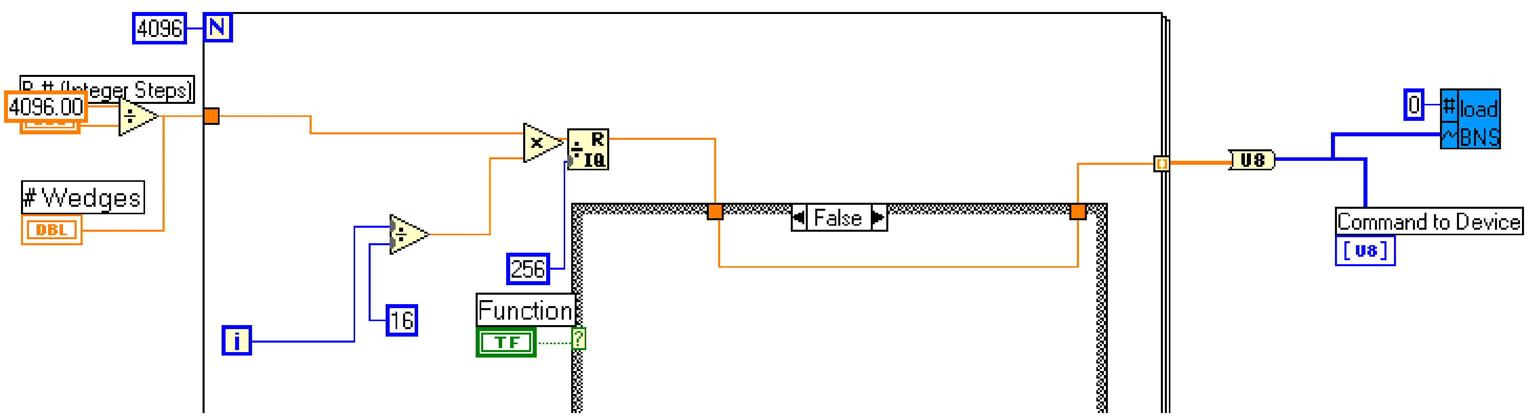
LabVEW Based Controller for Beam Steering

- 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 Creation - Using LabVIEW

- The voltage settings given to the device are created within the VI using:



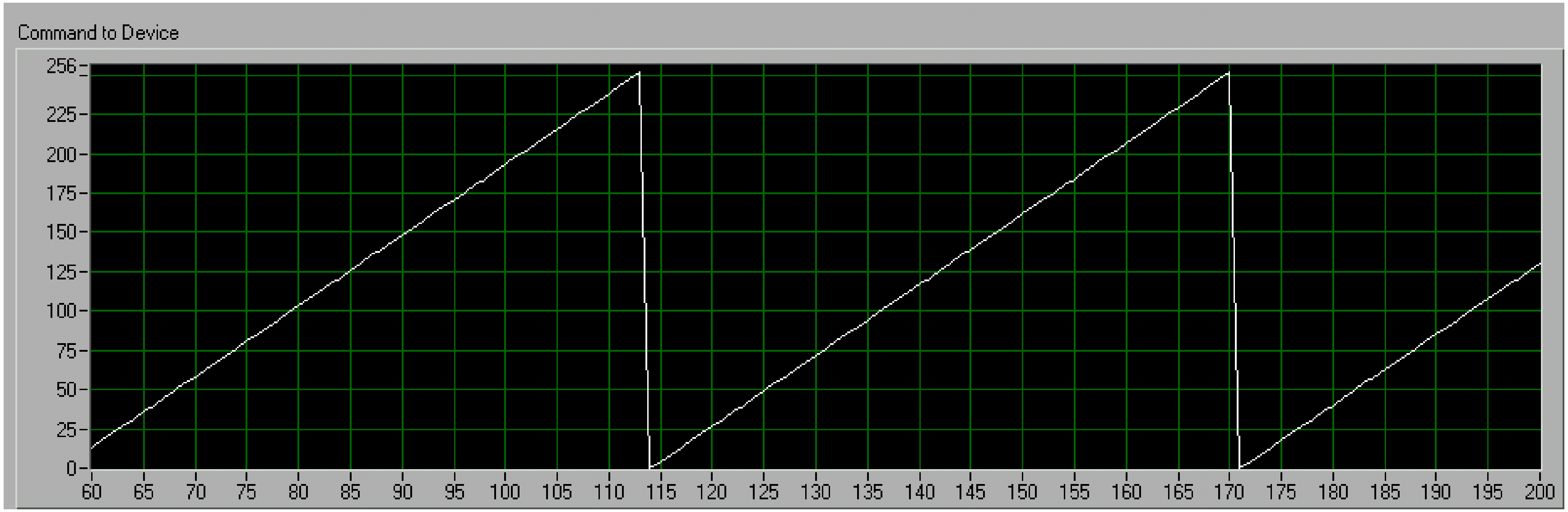
Or in mathematical form:

$$\mathrm{floor}\left[256\cdot\frac{\left(i-\mathrm{floor}\left(\frac{1}{N}\cdot i\right)\cdot N\right)}{N}\right]$$

N = Integer Determining Angle

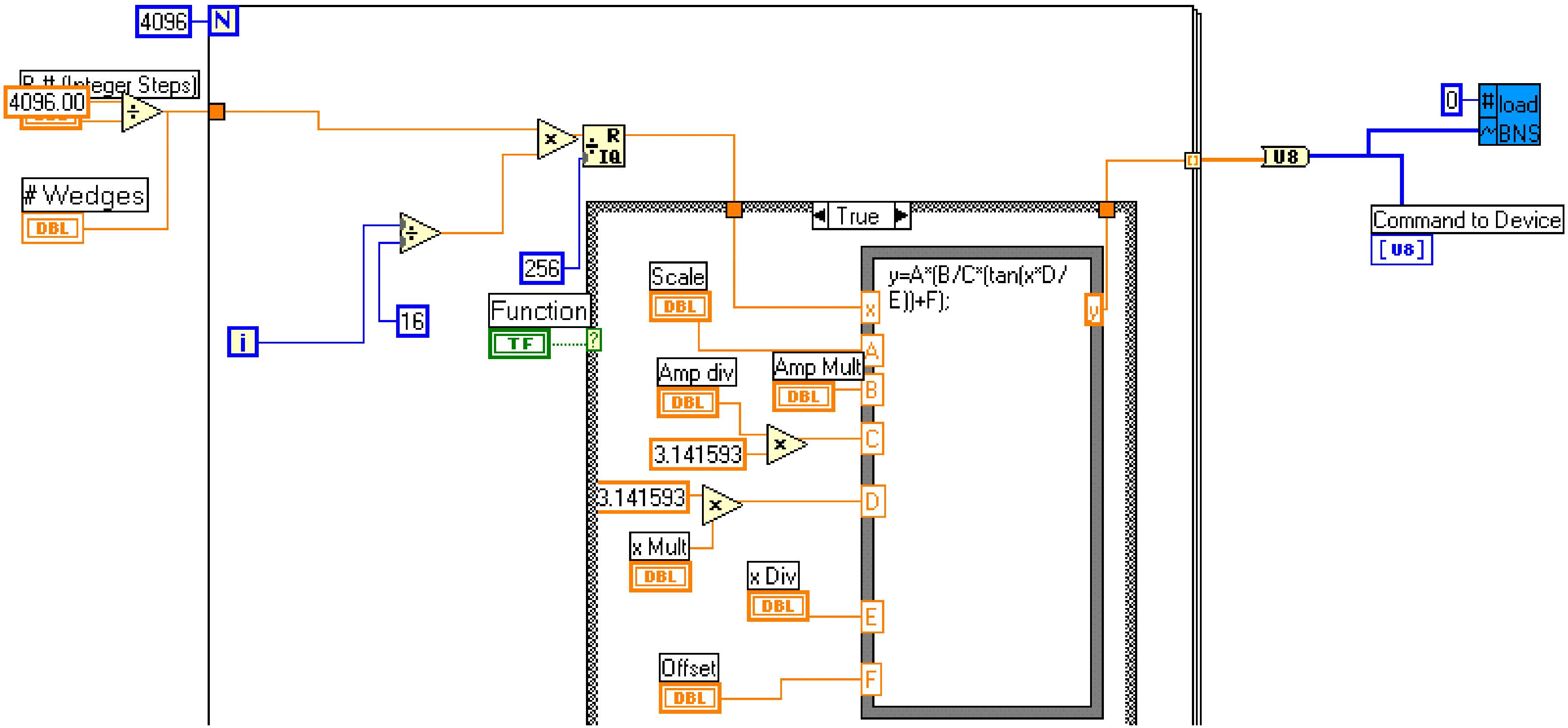
Sawtooth Profile

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



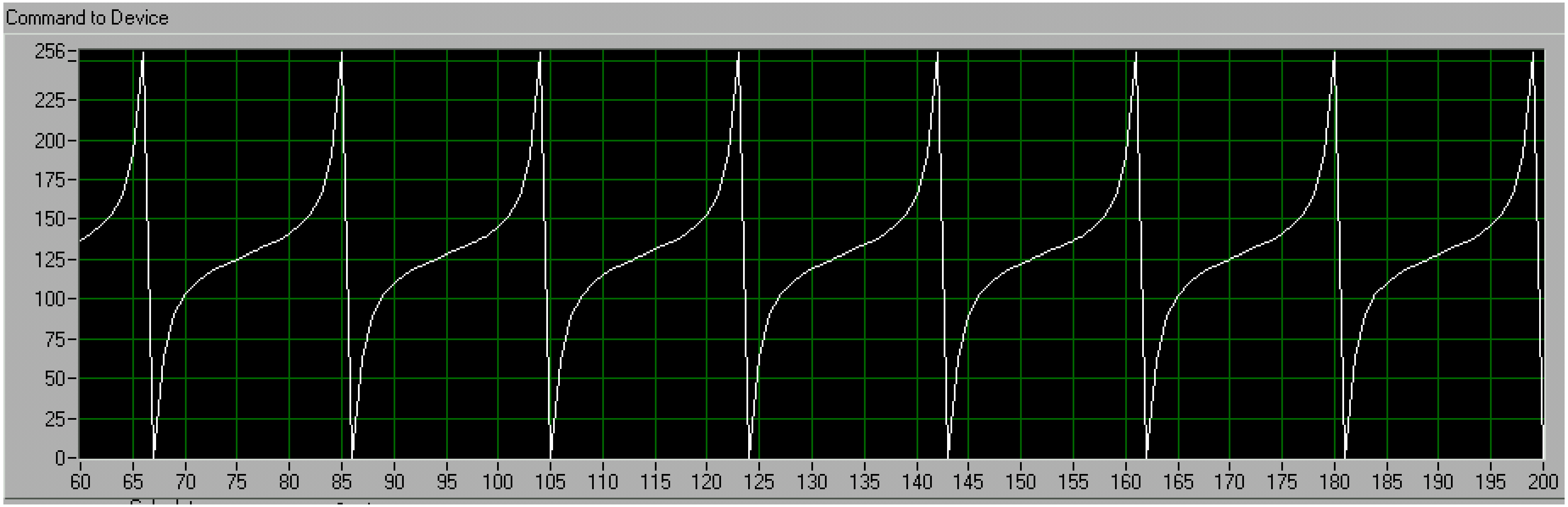
*The input value is proportional to the number of gratings on the device.

Creation of Modified Profiles: the tangent function



Tangent Profile

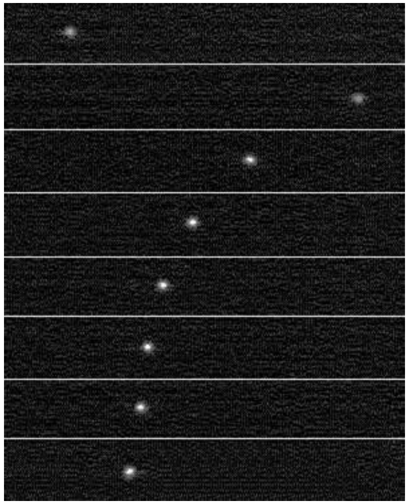
- For optimal results, parameters must be chosen such that the entire range of 0-256 is used with 0 and 256 occurring with a consistent period.
- The selected parameters are unique for each angle.



Specification	High-voltage SLM
Aperture Size	≥ 19.0mm x 19.0mm
Resolution	12,160 x 1 (all independently addressed)
Pixel Pitch	≤ 1.6 µm
Efficiency	> 90% @ 0° > 60% @ ± 10° for λ > 1 µm
Data refresh rate	> 10,000 frames per second
New-data frame rate	1,000 frames per second
Modulation	0 to 2π for 530nm <λ < 2060nm
LC response time for 2π stroke	< 1 millisecond
Gray-scale addressing	8 bits per pixel
Signal levels	0 to 12 volts

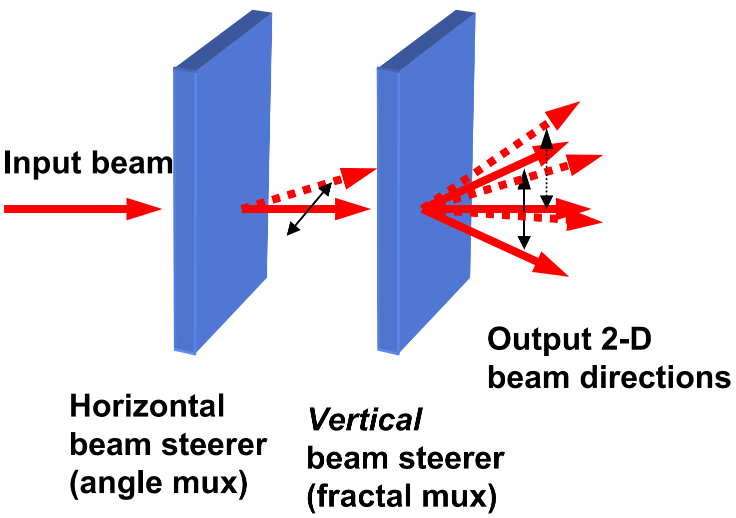
Example of Beam Steering Results

- -0.75°
- +3.00°
- +1.50°
- +0.75°
- +0.38°
- +0.19°
- +0.09°
- +0.00°



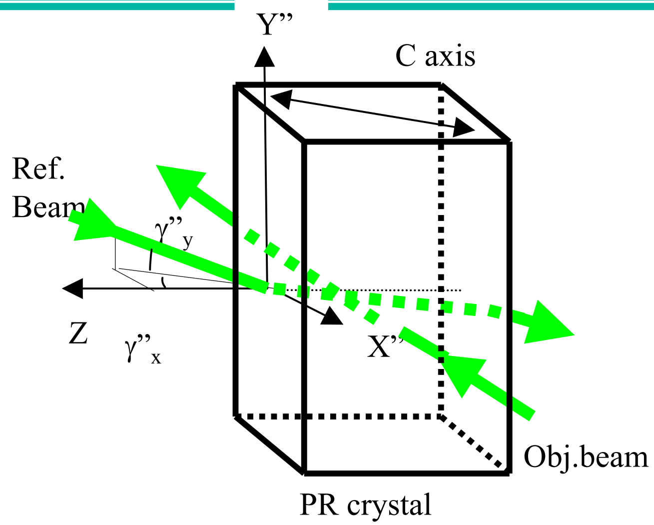
Beam Steering Results

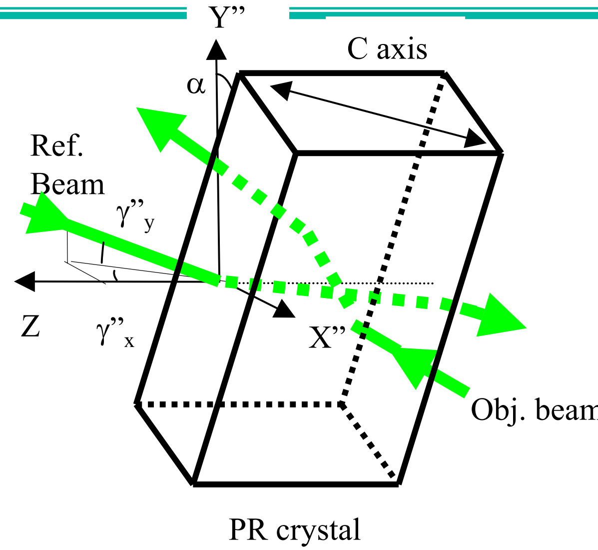
2-D (Fractal-)angle Multiplexing Using Cascaded SLM Beam Steering Devices



Schematic of cascading two SLM-based BS devices to achieve 2-D (fractal-)angle mutliplexing recording

New $LiNbO_3$ PR Crystal Orientation Optimizing 2-D Holographic Data Recording Density



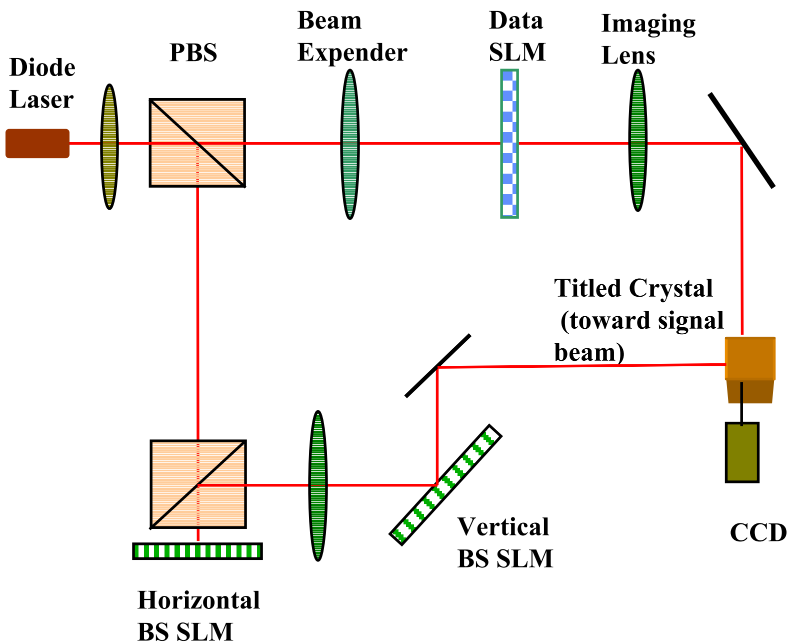


- **Original photorefractive crystal orientation**
  - **Optimum recording density only with reference beam steered around one axis (X’’-axis, as shown)**
  - **Number of holograms recorded in x”direction is *10* times larger than that recorded in Y’’ (or the fractal direction)**
- **New PR crystal orientation**
  - **Crystal tilted by 20 degree ($\alpha \approx 20°$) off the Y”-axis**
  - **Permit propagating waves be decoupled and form two set of gratings that optimizing recording density in both X’’ and Y’’ direction two wave decoupling**
  - **Result in equal number of holograms recordable in both X’’ and Y’’ direction**
  - **Increase recording density by 10 folds**

- **Optimized the crystal recording orientation:**

  Crystal titled about 20^{O} toward the signal beam has been found optimal in terms of minimizing the cross-talk in vertical direction.

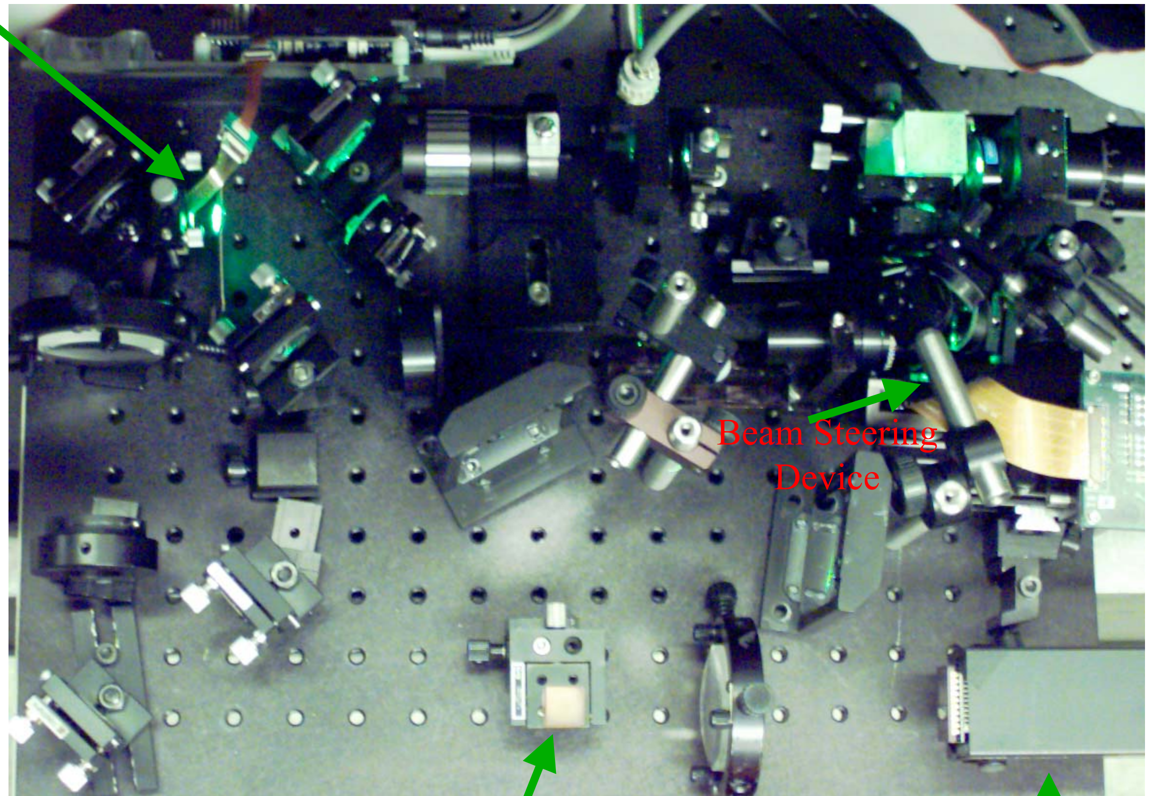
  ==> Increased number of holograms recordable in the vertical direction by 10 folds



System architecture of 2-D (fractal-)angle multiplexing recording

Book-sized Holographic Memory Breadboard

Input Spatial Light Modulator

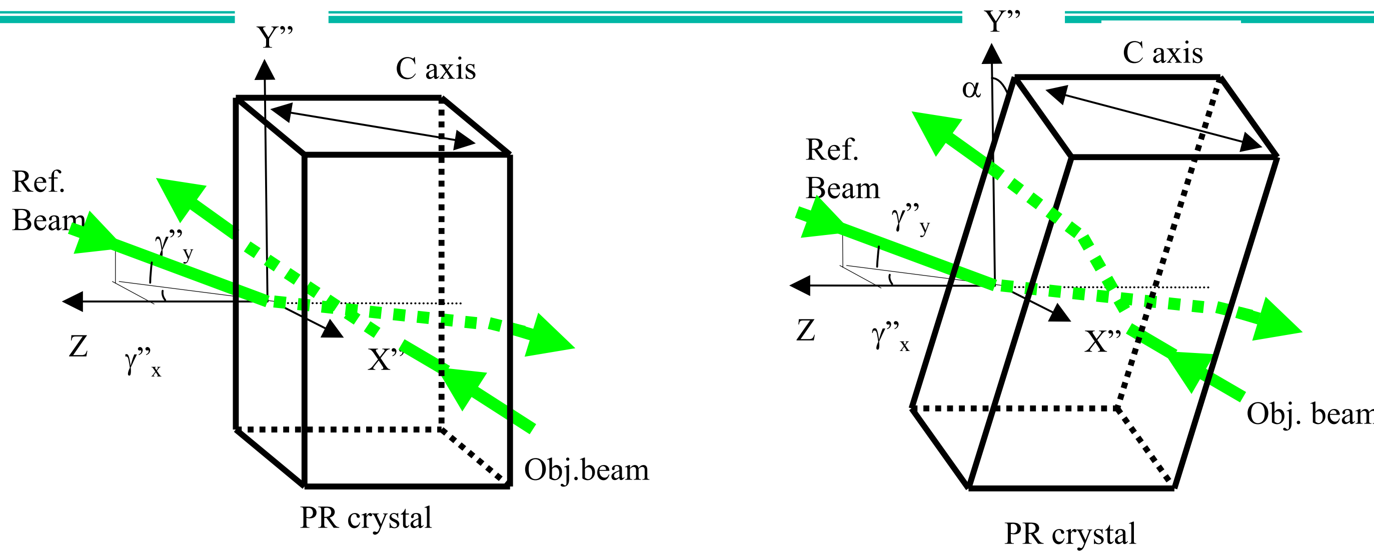


$LiNbO_3$ Photorefractive Crystal

CCD Detector

Photograph of a JPL compact holographic memory breadboard developed under NASA sponsorship

New $LiNbO_3$ PR Crystal Orientation Optimizing 2-D Holographic Data Recording Density



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  - **Optimum recording density only with reference beam steered around one axis (X''-axis, as shown)**
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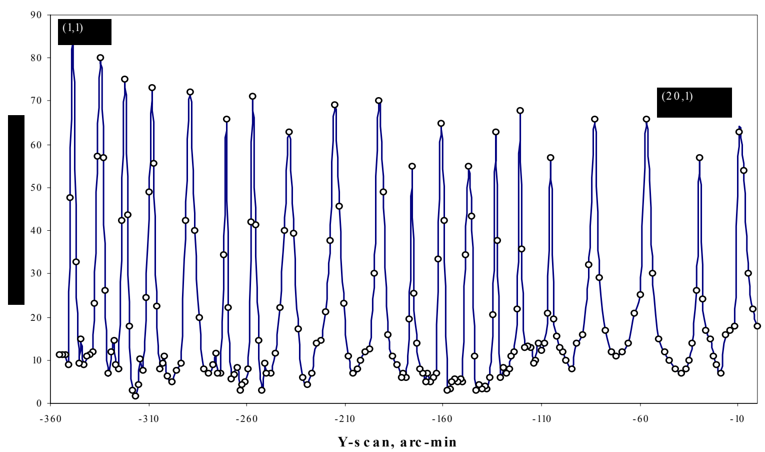
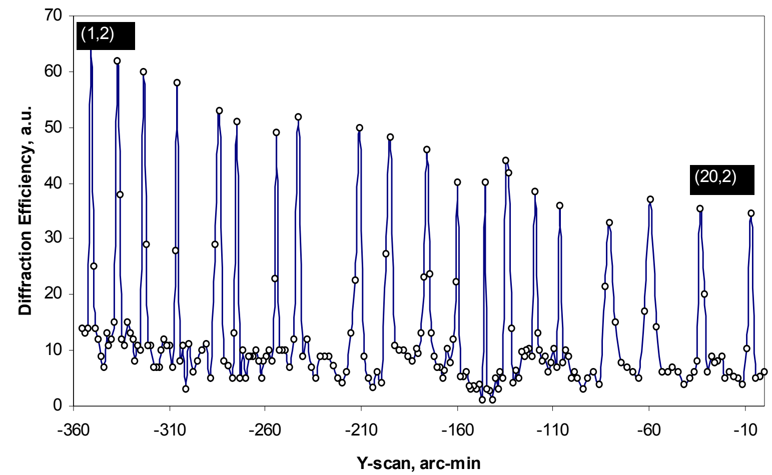
- **New PR crystal orientation**
  - **Crystal tilted by 20 degree ($\alpha \approx 20°$) off the Y"-axis**
  - **Permit propagating waves be decoupled and form two set of gratings that optimizing recording density in both X'' and Y'' direction two wave decoupling**
  - **Result in equal number of holograms recordable in both X'' and Y'' direction**
  - **Increase recording density by 10 folds**

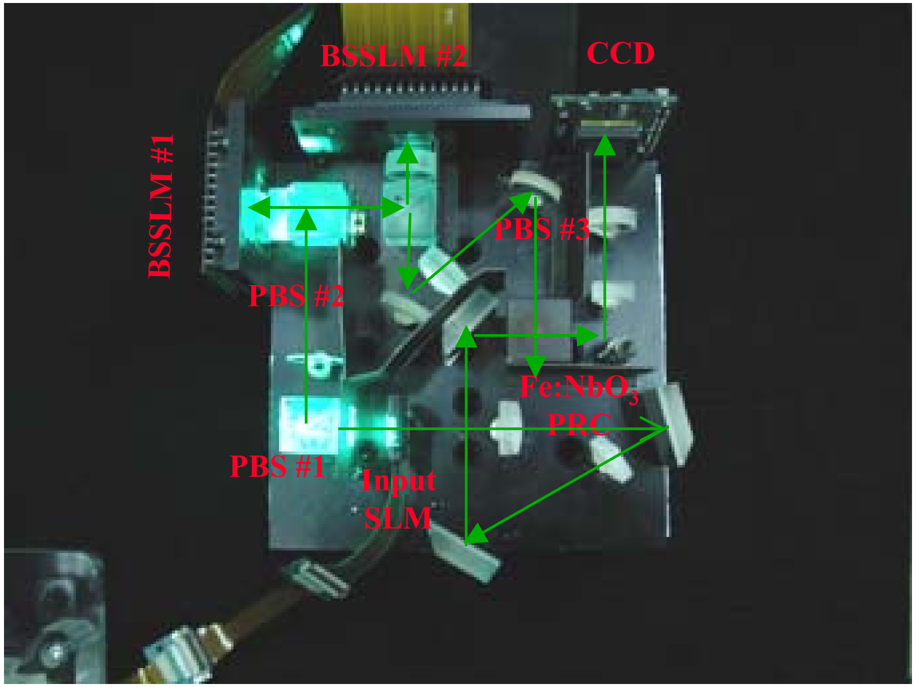
Recent Experimental Investigation of Holographic Storage Density with 2-D Scanning





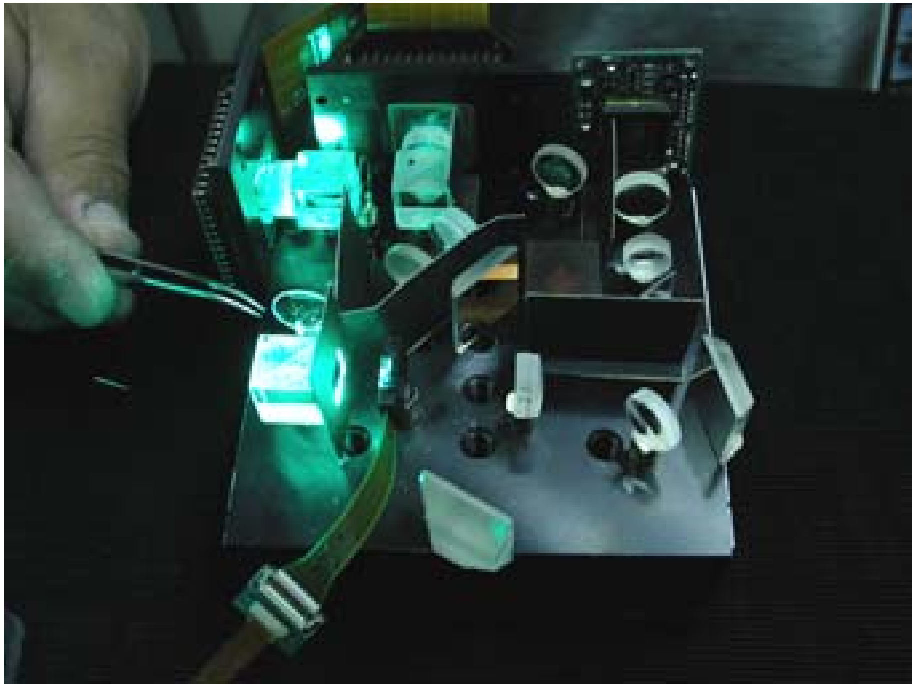
- Designed system architecture to extend holographic data storage from 1-D to 2-D spatial multiplexing
- Identified experimentally the optimum PR crystal orientation for high-density holographic data storage in two orthogonal dimensions
- Ready to modify the holographic memory breadboard to 2-D full-capacity holographic data storage

CD Driver – Sized
Advanced Holographic Memory Breadboard

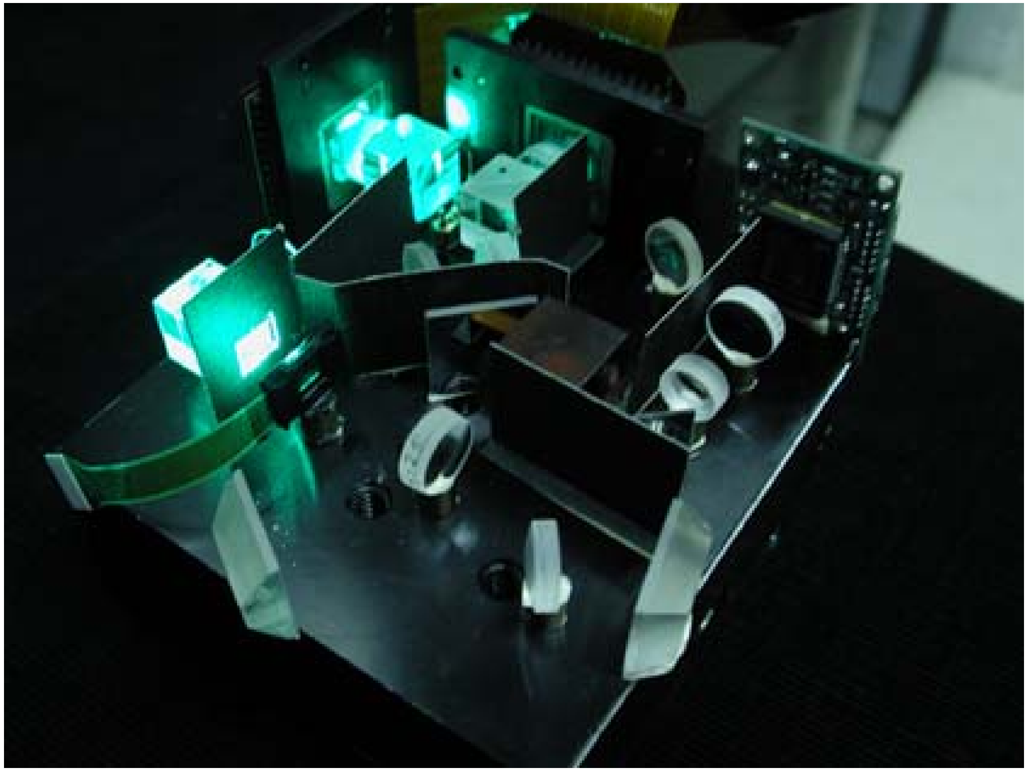


Volume: 10 cm x 10 cm x 1 cm

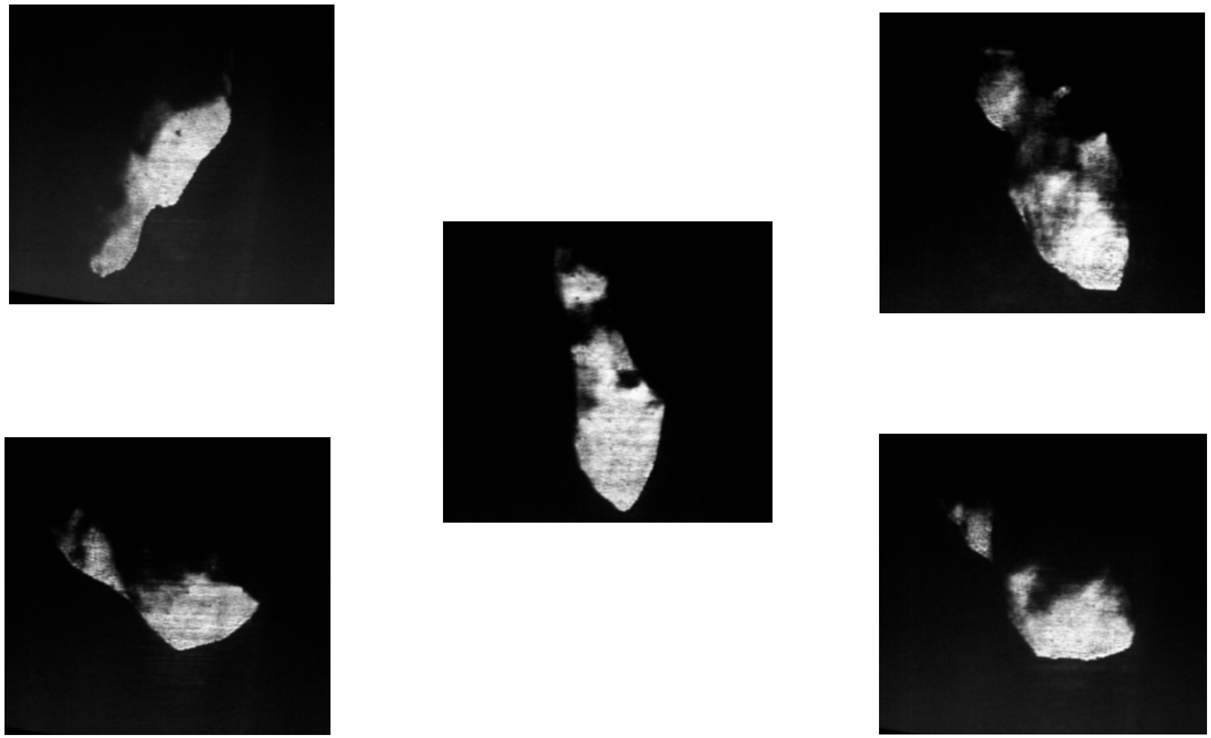
CD Driver –sized
Advanced Holographic Memory Breadboard



- Fine tuning of a CD driver-sized holographic memory breadboard prior to data recording/retrieval



Holographically Retrieved Grayscale Images - Asteroid Toutatis



Experimental results showing retrieved holographic images of a Toutatis Asteroid

Summary

(We have developed a new 2-D (Fractal-)Angle multiplexing using 2 cascaded Liquid Crystal Spatial Light Modulator Beam Steering devices to enable high-speed, random access beam steering for angularly multiplexed hologram recording without any moving parts

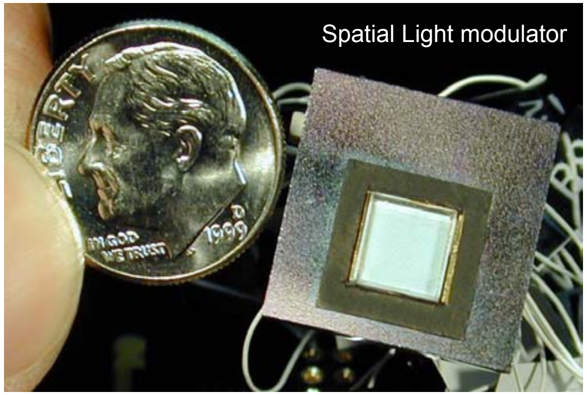
- We have developed a compact CHDS breadboard and demonstrated grayscale holographic data storage/retrieval

- Holographic data storage, upon full development, will simultaneously satisfy all space data storage reqireemnts in nonvolatility (decades), radiation-resistance, high-density (Tbs), low volume (regular memory card-size), high transfer rate (1 Gbs/sec),, read/rewritable, random access W/O moving parts

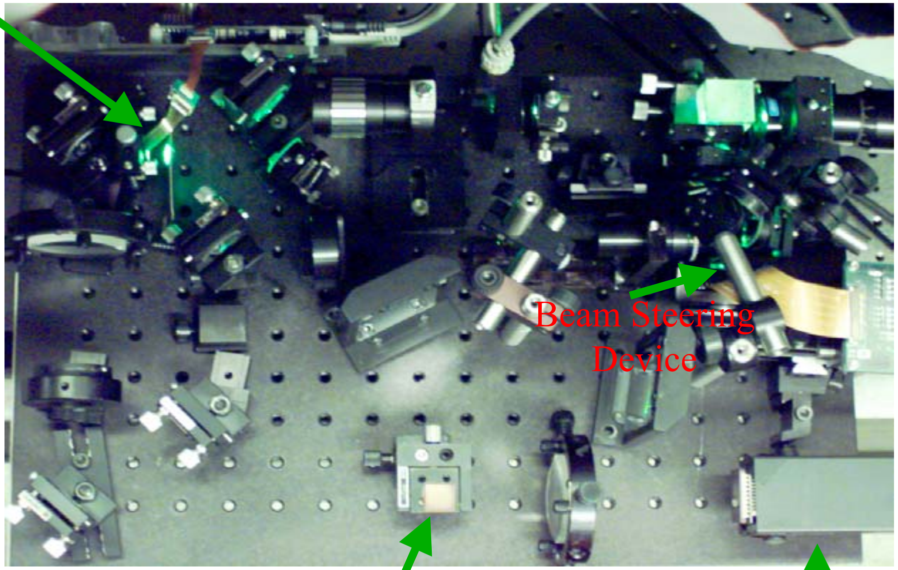
Advanced Holographic Memory (T. Chao)

Description and Objectives

- **Develop innovative holographic memory technology to enable real-time mass data storage/retrieval in space environment**
- **Demonstrate key capabilities:**
  - High data storage capacity (up to 10GB/module)
  - High random access data transfer rate (up to 1GB/s)



Input Spatial Light Modulator



Book-sized holographic memory breadboard

$LiNbO_3$ Photorefractive Crystal

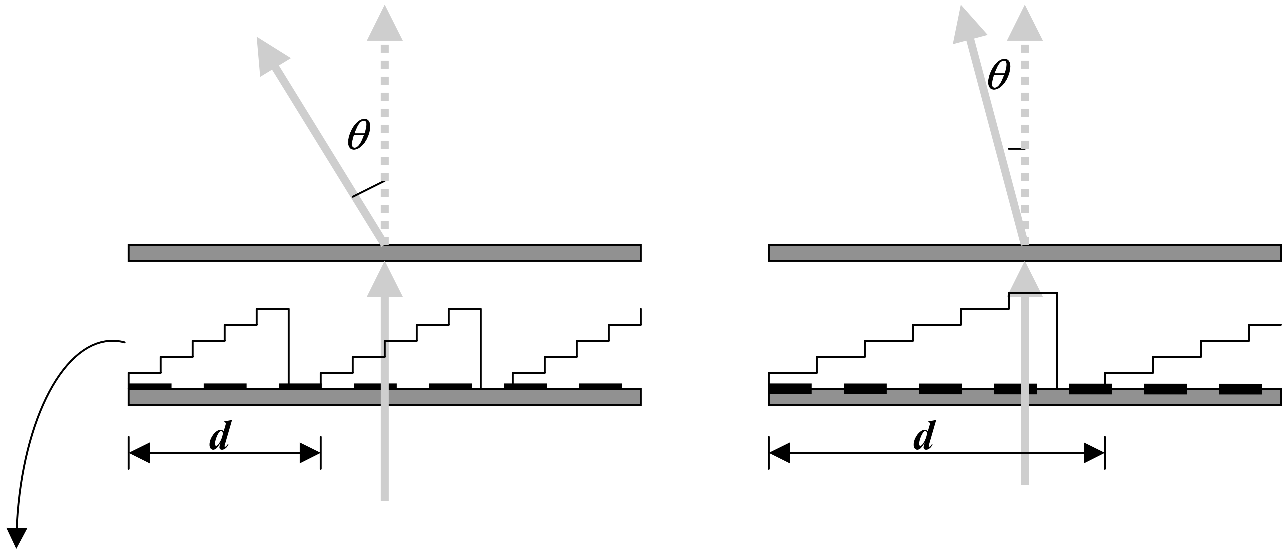
CCD Detector

FY '01 Accomplishments

- **Developed a compact holographic memory breadboard**
- **Performed system optics design to optimum data recording/retrieval performance**
- **Assembled a book-sized holographic breadboard**
- **Successfully demonstrated holographic data recording and readout of movie clip of grayscale images**

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-2π ramp w/ a period *d* which determines the deflection angle θ

Doubly Doped $LiNbO_3$ PR Crystal

- **Recently, more doping ions have been investigated for nonvolatile performance in a doubly-doped (2-color) $LiNbO_3$ crystal**
  - **Iron group (Ti, Cr, Mn, Cu)**
  - **Rare-earth element ions (Nd, Tb)have been investigated for nonvolatile performance in a $LiNbO_3$ crystal. To date, it has been reported that doubly doped $Cr:Cu:LiNbO_3$ as well as Fe: $Tb:LiNbO_3$ are effective in nonvolatile holographic recordings.**
- **A holographic memory testbed will be assembled for testing the nonvolatile data storage capability of candidate 2-photon PR crystals**
  - **Fe:Mn: $LiNbO_3$, Cr:Cu: $LiNbO_3$, and $Fe:Tb:LiNbO_3$, and Ce:Mn: $LiNbO_3$)**

Radiation Sources in Space

- **Major types of radiation that are potentially hazardous to memory systems (electronic and holographic) include:**
  - higher energy photon (X-ray, gammas),
  - neutrons,
  - and charged particles (electrons, protons, alpha particles, heavy ions)
- **The parameters, which determine the amount of damage introduced by a particle,**
  - Rest mass (e.g. zero for protons),
  - Energy and the charge state (e.g. electronics are negative, protons and alphas are positive. Ions can even be multiply charged).

Radiation Damages to $LiNbO_3$ PR Crystal - Previous Studies

Types of Damages / Source of Radiation	Refractive index (Δn_o) changes	Density changes	Spectral absorption
X-rays, g-rays	$\Delta(n_o)$ increases with dose	None	Spectral absorption in blue spectral region observed
Neutrons/charged particles	Decrease with dose	Volume increases at very high nuclear deposited energy	None

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

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
thickness	√	√	√	*	*	√
shrinkage	no	no	no	yes (3%)	yes (3%)	yes (2%)
wavelength	488nm	red+UV	red+blue	532nm	630-670nm	488nm
need fixing	yes	no	no	no	no	no
dynamic range	large	large	large**	modest	modest	modest
wiring speed	slow	very slow	slow**	very fast	fast	fast
rewritable	yes	yes	yes	no	no	no

* 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,

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

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
M/#	10*	10	30**	6	5	5
η_h	2.5×10^{-7}	10^{-6}	10^{-5}**	3.6×10^{-7}	2.5×10^{-7}	2.5×10^{-7}

* The M/# drops approximately by a factor of 2 after thermal fixing in $LiNbO_3$:Fe.
** Projected value.

1. Photon-limited readout: $N_e = \eta_{tr}\eta_q \frac{\eta_h \eta_{im} P_{in}}{h\nu} \frac{1}{r_{ON} N_p} t_{int}$

Variable	Definition	Value
Ne	number of signal electrons	~25,000*
η_{tr}	electron transfer efficiency	0.9**
η_q	quantum efficiency	0.9
η_h	hologram diffraction efficiency	**From above**
η_{im}	efficiency of readout optics	0.9
P_{in}	readout power	**?**
hν	power per electron	4.073×10^{-19} J
r_{ON} N_p	number of ON pixels	0.5×10^{6} ***
t_{int}	integration time	1 sec.

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

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

*** Exact number for binary random-bit patterns.

* Projected value

Readout powers for 1-second integration time

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
P_{in} (mw)	28	7	0.07*	19	28	28

Recording speed

1. recording speed for 10,000 holograms (target diffraction efficiency is 10^{-7}).

	LiNbO3 Fe	LiNbO3 Fe, Mn	LiNbO3 Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
Writing energy mJ/cm^2	3	100*	1**	0.1	1	1
Writing intensity mw/cm^2	100	333*	33**	3.3	80	80

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

Holographic Memory Development Roadmap and Major Applications

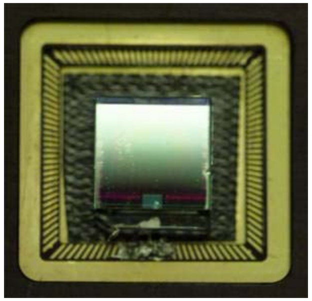
ROADMAP FOR CHDS DEVELOPMENT PLAN

- **CHDS advanced system development: To develop and demonstrate a compact, nonvolatile, holographic data storage system for onboard data storage and support of intelligent system**
  - Miniaturization
    - » Utilized OEIC technology to integrate key components (VECSL laser array, spatial light modulator, active pixel sensor, and MEMS micro-mirror into a 1 inch^3 holographic memory module.
  - Non-volatility
    - » Replace current 1-dopant photorefractive recording material (e.g. Fe:$LiNbO_3$ with emerging 2-dopant materials (e.g. Fe:Mn: $LiNbO_3$, Cr:Cu: $LiNbO_3$, and Fe:Tb:$LiNbO_3$, and Ce:Mn: $LiNbO_3$) to *extend the holographic data storage shell life from months to decades*

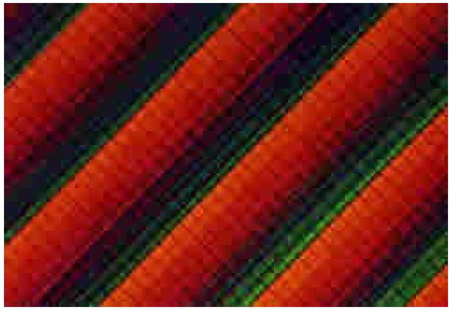
MAJOR APPLICATIONS

- **Enable onboard data storage on EOS satellite (requiring up to 1 TB data storage per day)**
- **Enable real-time continuous recording of video imageries during fly-by or planet orbiting**
  - » **Neptune Orbiter With Triton Flybys ; Saturn Ring Observer; Mars missions**
- **Enable high-density data storage onboard deep-space spacecraft in *radiation-intensive* environment**
  - » **EUROPA mission**
- **Enable intelligent data search/retrieval using cross-association capability of holographic memory**

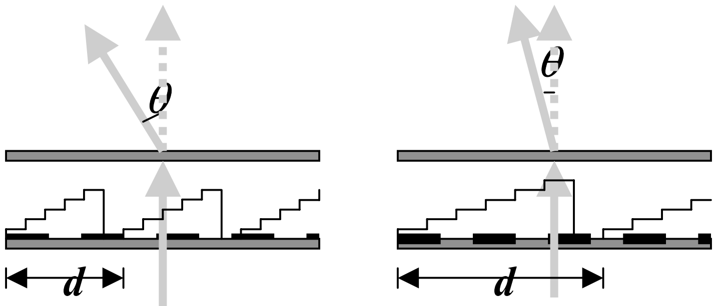
Beam Steering Spatial Light Modulator



Picture of a liquid crystal Beam steering device



Surface phase-modulation profile of a beam steering device



Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-2π ramp w/ a period *d* which determines the deflection angle θ

- Utilized a new Electro-optic beam steering device
  - Custom designed a liquid crystal beam steering device operational at 514 nm
  - Fabricated this device at Boulder Nonlinear system Inc.
  - Designed a LabView-based phase array profile controller
  - Achieved a more than 75% diffraction efficiency
  - 128 resolvable scanning spots with the current design
    - » Can be increased by 10-fold with larger aperture size
  - Capable of storing more than 15,000 pages of holographic data can be stored using a pair of orthogonally cascaded beam steering devices
    - » Storage capacity up to 250 Gb per holographic memory cube

Future Plans

- **JPl will collaborate with Caltech and Academia todevelop two-photon doubled doped photorefractive material for long-term nonvolatile data storage (increase the memory shelf life from months to decades)**
  - **Recently, more doping ions have been investigated for nonvolatile performance in a doubly-doped (2-color) $LiNbO_3$ crystal**
    - **Iron group (Ti, Cr, Mn, Cu)**
    - **Rare-earth element ions (Nd, Tb)have been investigated for nonvolatile performance in a $LiNbO_3$ crystal. To date, it has been reported that doubly doped $Cr{:}Cu{:}LiNbO_3$ as well as $Fe{:}\ Tb{:}LiNbO_3$ are effective in nonvolatile holographic recordings.**
  - **Comprehensive radiation test of the new photorefractive material to validate its radiation-resistance**
- **JPL will insert the new nonvolatile 2-photon PR crystals (e.g.** $Fe{:}Mn{:}LiNbO_3$, $Cr{:}Cu{:}\ LiNbO_3$, and $Fe{:}Tb{:}LiNbO_3$, and $Ce{:}Mn{:}\ LiNbO_3$) **material into the CHDS breadboard to demonstrate nonvolatile data storage.**
- **JPL will investigate the extend the use of holographic memory technologies for muti-channel demultiplexing in telecommunication systems**
  - **The inherent wavelength selectivity will enable new massively parallel optical communication system development**

Motivation, Challenge, and Benchmark

Motivation

Space Science Enterprise

- Current data storage capacity onboard spacecraft is limited (100's MB), it is far less than that
required for real-time recording of video imageries during fly-by or planet orbiting (e.g. Neptune Orbiter With Triton Flybys ; Saturn Ring Observer; Mars missions)
- No current data storage technology is survivable in *radiation-intensive* environment such as that over the Europa

Earth Science Enterprise

- Current Earth orbiting satellites (for EOS) requires 10's of Terabytes onboard storage capacity for buffer storage of data from high-rate sensors (SAR, LADAR, etc) prior their downlink to Earth.
- Magnetic data storage system is far inadequate due to its high mass and high volume

Enable onboard data storage on EOS satellite (requiring up to 1 TB data storage per day)
Enable intelligent data search/retrieval using cross-association capability of holographic memory

Challenges

Develop high-capacity, high-transfer rate, nonvolatile, radiation-resistant holographic data storage

Motivation, Challenge, and Benchmark - Continued

PERFORMANCE METRICS OF READ/REWRITABLE NONVOLATILE MEMORY TECHNOLOGIES

Feature	Magnetic	Flash	Holographic
Non-volatile	Yes	Yes	yes
Data Retention	> 10 yrs	> 10 yrs	> 10 yrs
Endurance (Erase/write Cycles)	10^5	10^6 (commercial)	unlimited
Data Transfer rate	10 Mb/sec	160 Mb/sec	> 1 Gb/sec
Power Consumption	1Gb/Watt	10 Gb/watt	100 Gb/watt
Current Package	6 x 3.5-in disk < 100 GB	256 Mb & 512 Mb (per die) 100's Gb (MCM)	100 Gb/cm^3 cube. 1 Tb/card

BENEFIT TO NASA

- **NASA's 21st century missions will**
  - require the storage of large volumes of data
  - be subject to long-duration exposure to the space radiation environment
- **be based on integrated miniature systems**
  - This system is envisioned to be smaller than 1 cm^3 in volume.
- ***Holographic data storage technology* will simultaneously satisfy NASA's missions requirements in non volatility , high-density, high-transfer rate, low-power/volume, and and radiation-hardened.**