Holographic Memory Using MEMS Mirror Beam Steering Technology

Tien-Hsin Chao, Tien-Hsin.Chao@jpl.nasa.gov
Jay Hanan, Jay.C.Hanan@jpl.nasa.gov
George Reyes, George.F.Reyes@jpl.nasa.gov
Hanying Zhou, Hanying.Zhou@jpl.nasa.gov
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099

Abstract— We describe the development a high speed, high data rate holographic memory system using a photorefractive crystal as the storage media at JPL. Recently, the use of a newly developed MEMS mirror as the high-speed beam steering device has been investigated. The low-mass, low-volume, high-speed features of the MEMS mirror would enable the integration of a very compact holographic memory module for high speed holographic data storage and retrieval. The system architecture, MEMS mirror characterization data, and experimental investigation results will be presented. Recent radiation test results on a $Fe:LiNbO_3$ photorefractive crystal will also be reported.

TABLE OF CONTENTS

1. INTRODUCTION

JPL is currently developing a new holographic memory system with performance characteristics including: read/rewrite capability, high-density, high transfer rate, non-volatility, compactness, and radiation resistance. These characteristics are selected to meet requirements for data storage needs for both NASA's space missions and commercial applications [1-4].

NASA's future missions would require massive high-speed onboard data storage capability to support Earth Science missions. With regard to Earth science observation, a 1999 joint Jet Propulsion Laboratory and Goddard Space Flight Center (GFSC) study ("The High Data Rate Instrument Study") has pointed out that the onboard science data (collected by high date rate instruments such as hyperspectral and synthetic aperture radar) stored between downlinks would be up to 40 terabits (Tb) by 2003. However, onboard storage capability in 2003 is estimated at only 4 Tb that is only 10% of the requirement. By 2006, the storage capability would fall further behind that would only be able to support 1% of the onboard storage requirements.

2. COMPACT HOLOGRAPHIC MEMORY USING ELECTRO-OPTIC BEAM STEERING

- Beam Steering Spatial Light Modulator

The key to achieve high-speed data transfer rate in a holographic memory system is the laser beam steering methodology. In a previous effort, we have utilized the Liquid Crystal Beam Steering Spatial Light Modulator (BSSLM), developed by the Boulder Nonlinear Systems Inc. (BNS), for high-speed beam steering. This device is built upon a VLSI back plane in ceramic PGA carrier. A 1-dimensional array of 4096 pixels, filled with Nematic Twist Liquid Crystal (NTLC), is developed on the SLM surface. The device aperture is of the size of 7.4 μm x 7.4 μm, each pixel is of 1.8 μm x 7.4 μm in dimension.

The principle of operation of this BSSLM is illustrated in Figure 1. Since the SLM is a phase-modulation device, by applying proper addressing signals, the optical phase profile (i.e. a quantized multiple-level phase grating) would repeats over a 0-to-2π) ramp with a period d. The deflection angle q of the reflected beam will be inversely proportional to d:

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

Where λ is the wavelength of the laser beam. Thus, beam steering can be achieved by varying the period of the phase grating

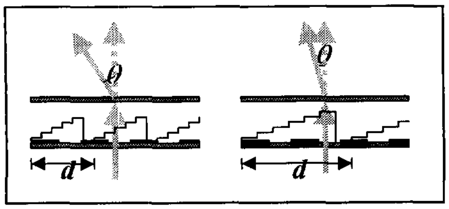
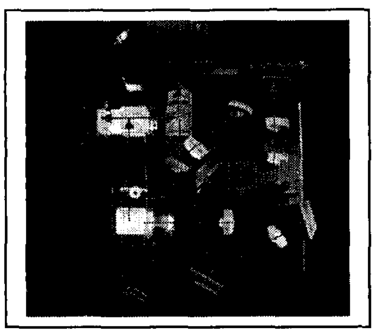
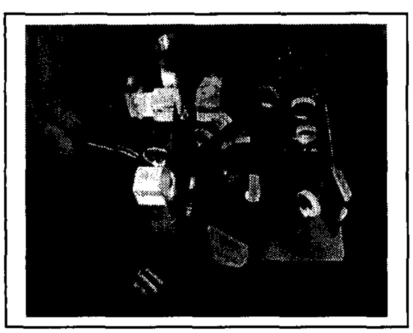


Figure 1. Beam steering using a phase modulation SLM with variable grating period.

Due to the compact size of the BSSLM, a very compact holographic memory breadboard has been developed at JPL. This CD-sized holographic memory breadboard, measuring 10 cm x 10 cm x 2.5 cm, is the most compact holographic memory module developed to date. The compact size of the VLSI based BSSLM together with advanced optics design has enabled the drastic reduction in the system volume from book-size to CD-size. A photo of this breadboard is shown in Figure 2.



(a)



(b)

Figure 2. Photos of JPL Developed Compact Advanced Holographic Memory Breadboard of the size of a CD-sized (Volume of 10 cm x 10 cm x 2.5 cm, or 4" x 4" x 1") using an E-O Beam Steering Technology with an Angular-Fractal Multiplexing Scheme.

- MEMS mirror for high-speed beam steering

Although the LC BSSLM phase array has been successfully utilized for high-speed beam steering in a compact holographic memory breadboard. The light throughput efficiency has to be further improved. Due to the light diffraction of the throughput light beams by the phase array in a LC BSSLM, there are many diffracted orders other than the first order of diffracted laser beam that is used for hologram recording. Since it is very difficult to achieve 100% diffraction efficiency in the first order, considerable amount of laser beam energy is spread into the zero order and high order of diffraction. The high-order of diffracted light beams cause spurious interference that often reduce the signal-to-noise ratio of the recorded holograms.

Therefore, we have recently investigated the use of high-speed scanning mirror that utilize light deflection instead of diffraction as the beam steering device. As shown in previous technical reports, galvanometer controlled mirrors have been used for laser beam steering applications. However, the considerable mass of the galvanometer mirror will severely limit its scanning speed (e.g. no more than video rate). Recently, we have investigated the use of emerging MEMS (Microelectromechanical Systems) mirror technology for high-speed beam steering in a compact holographic memory system.

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

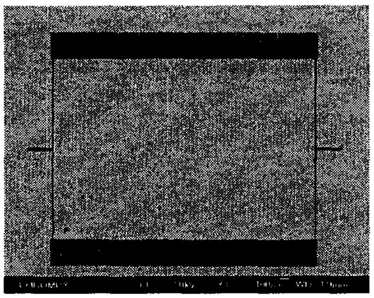
MEMS Micro-mirrors are mirrors that have been "shrunk" down to the microscopic world. Lately, the design and fabrication of micro-mirrors has received much more attention than in the past. This has been applied to the field of fiber optics. The MEMS Micro-mirrors could also be utilized for beam steering in a holographic memory system.

.

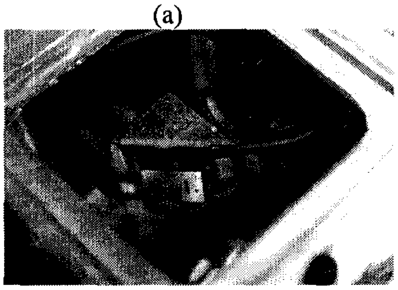
The fabrication method for these micro-mirrors is exactly the same as for a cantilever structure except after the process is completed, a reflective layer, such as aluminum, must be placed on top of the beam.

A MEMS micro-mirror utilizes electrostatic actuation for mirror steering. Since positive and negative charges attract each other (and like charges repel), if a cantilever can be made to keep a positive charge while placing an alternating positive-negative charge above it, then by electrostatics, the cantilever will resonate up and down.

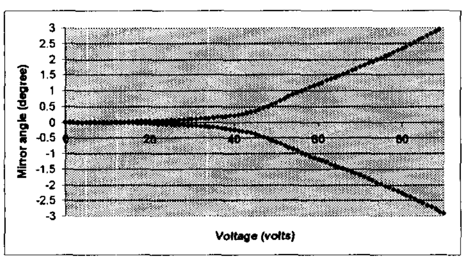
Due to the rapid recent development in MEMS technology, a MEMS mirror is becoming very attractive as the beam steering device in a holographic memory system. Advantages include: high light throughput efficiency (> 99% reflectivity), superior beam quality (light reflected from a mirror does not generate spurious diffraction as that of a diffractive beam steering device), low mass and high-speed. JPL is currently experimentally investigating the utilization of such a MEMS mirror as the beam steering device in a holographic memory system. Photos of a candidate MEMS mirror, the packaged system, and its corresponding driving voltage pattern is shown in figure 3(a) through 3(c) respectively.



(a)



(b)



(c)

Figure 3. (a) Photo of a candidate MEMS mirror; (b) photo of the packaged MEMS mirror system; and (c) characteristic driving voltage.

The holographic memory system architecture utilizing the MEMS mirror for beam steering is shown in Figure 4. Details of system layout are as follows: a collimated laser beam first enters a polarizing beam splitter, and on exit, is split into two beams. The input beam subsequently passes through the data SLM (spatial light modulator), an imaging relay lens pair L_1 and L_2, then impinges on an Iron doped Lithium Niobate (Fe:$LiNbO_3$) photorefractive crystal (PRC). The imaging relay lens pair L_1-L_2 is used to scale the imaging size of the input SLM to match that of the input pupil of the PRC. It will also sharply image the input SLM image onto the recording plane of a CCD placed behind the PRC. The PRC is the holographic recording device capable for large capacity, rewriteable, holographic memory recording. The other beam (i.e. the reference beam) will first pass through the imaging relay lens pair L_3-L_4 before impinging upon the MEMS mirror. The laser beam will then be deflected by the MEMS mirror by a pre-determined incremental angle. The deflected reference beam will continue to pass through the third imaging relay lens pair L_5-L_6.and reach the PRC. The reference beam and the data beam intersect within the volume of the PRC forming a 90° recording geometry. Focal lengths and aperture size of the lens pair L_3–L_4 is selected to compensate the scale difference between the input SLM aperture and that of the MEMS mirror. Similarly, the lens pair L_5–L_6 feature dimensions are selected to match the scale difference between the MEMS mirror and the PRC entrance pupil. The MEMS mirror will scan the reference beam along the horizontal plane (or the x-axis) in parallel with the C-axis. During holographic data recording, the deflected angle from the MEMS mirror is varied by a small increment with respect to each new data page. Thus, the interference pattern formed between each page of input data beam and the specifically oriented reference beam will be recorded in the PR crystal in an angular multiplexing scheme.

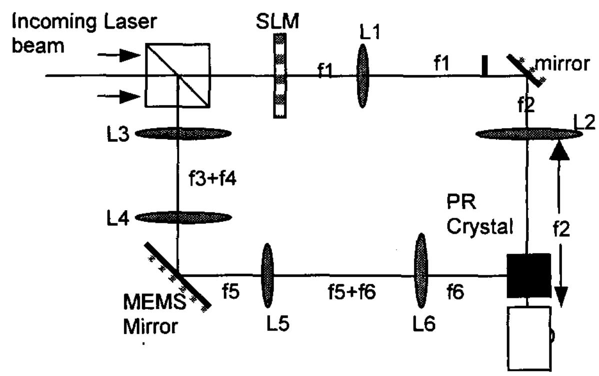


Figure 4. Schematic of a holographic memory system using a MEMS mirror for beam steering

During readout, the data beam will be shut down and the reference beam will be activated to illuminate the PR crystal. Due to the principle of holographic wavefront reconstruction, the stored page data, corresponding to a specific reference beam angle, will be readout. The readout data beam will be sharply imaged on to the CCD recording plane.

3. EXPERIMENTAL INVESTIGATION RESULTS OF THE RADIATION RESISTANCE of the Fe:$LiNbO_3$ PHOTOREFRACTIVE CRYSTAL

Advanced holographic memories for NASA space applications require not only high-density and high-speed data storage, but also high radiation resistance. Due to the inherent redundant nature and radiation self-shielding effect of volume storage, the holographic memories are expected to be radiation resistant.

We have recently conducted a quantitative experimental measurement of the radiation effect of Co^{60} Gamma Radiation on the stored hologram within Fe:$LinbO_3$ PR Crystal .

Prior to the radiation test, a grayscale image was written into Fe:$LiNbO_3$ crystal. During the recording, this crystal is placed in a precision holder. This crystal holder will ensure that holograms readout from the crystal, before and after the radiation test, is acquired under the same experimental setup parameters. This will ensure any deviation between the two readout hologram images is caused only by the radiation effect.

During gamma irradiation and transportation from one place to another, the crystal was cover with a thin polyethylene bag to protect against small particles from the air that may deposit on the crystal. Quantitative measurements on hologram as an image were performed using specialized software for image analysis, obtained from Scion. The program allows the selection of the image and performs an integrated density, which is the sum of the gray values in the selection, with background subtracted. It is computed using the following formula: Integrated Density = N * (Mean - Background) where N is number of pixels in the selection, and Background is the modal gray value (most common pixel value) after smoothing the histogram. Using integrated density approach for each irradiated hologram, In this way we get radiation hologram alteration parameter that is plotted in Fig 5.

As shown in Figure 5, holographic memory stored in Fe(0.10%):LiNbO3 crystal shows radiation resistance to Co^{60} gamma radiation. The radiation test performed at JPL, shows for the first time that the hologram recorded in a highly Fe doped crystal, about 0.10% wt. Fe, is very little affected by radiation with a dose up to 400 krad. Maximum change we observed in radiation-altered hologram, $\approx 2.5 \times 10^{-4}$ is reasonably low. This preliminary radiation test shows that the Fe:$LinbO_3$ photorefractive material at least four times more radiation resistant than its electronic counterpart.

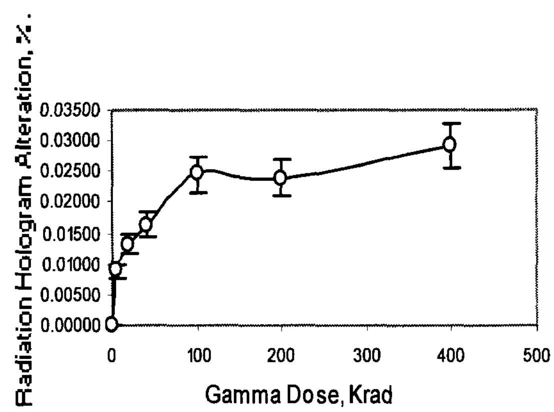


Fig.5 Hologram alteration due to gamma radiation effect.

4. SUMMARY

JPL has successfully developed an advanced holographic memory technology to enable high-density and high-speed holographic data storage with random access during data recording and readout. Two innovative E-O beam steering schemes: one utilized a liquid crystal beam steering device and the other utilized a MEMS mirror scanner. The LC device has recently been experimentally implemented. A CD-sized holographic memory breadboard has been integrated and demonstrated for successful holographic data recording and retrieval. This breadboard is the most compact one developed to date. More recently, an innovative high-speed beam steering technology using a MEMS mirror has also been selected and is currently under experimental investigation. Potentially, the high efficiency, compact MEMS mirror, will enable the development of an even more compact and high-density holographic memory system.

JPL has also performed radiation test on the key Fe:$LinbO_3$ photorefractive crystal. Gamma radiation test has been conducted on a series of the PR crystal with different doping concentrations. We have identified the proper doping level has exhibited the most radiation resistance performance. Follow-on radiation test is underway.

5. ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Dr. Danut Dragoi's assistance in carrying out the radiation test is acknowledged.

6. REFERENCE

1. Tien-Hsin Chao, Hanying Zhou, Geoerge Reyes, JPL "Compact Holographic Data Storage System,", Proceedings of Eighteenth IEEE Symposium on Mass

Storage Systems in cooperation with the Ninth NASA Goddard Conference on Mass Storage Systems and Technologies, April. 2001

2. T. H. Chao, H Zhou, and G. Reyes, "Advanced compact holographic data storage system," Proceedings of Non-volatile memory technology symposium 2000, pp. 100-105, November, 2000.

3. Tien-Hsin Chao, George Reyes, Hanying Zhou, Danut Dragoi, and Jay Hanan, "High-density Holographic Data Storage," Proceedings of International Symposium on Optical memory 2001 PP.248-249, Taiwan, Oct.2001.

4. Tien-Hsin Chao, George Reyes, Hanying Zhou, Danut Dragoi, and Jay Hanan, "Nonvolatile Rad-Hard Holographic Memory," Proceedings of Non-volatile memory Technology Symposium 2001, pp. 12-17, San Diego Ca, Nov. 2001.

5. Tien-Hsin Chao, "Advanced Holographic Memory_AIST-99-0057_Final Report" Prepared for NASA ESTO AIST, Nov. 2002.