LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-820996

MEMS Refocusing Secondary Concentrator for Free Space Optics, CRADA No. TC02073.0

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March 30, 2021

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

MEMS Refocusing Secondary Concentrator for Free Space Optics

Final Report
CRADA No. TC02073.0
Date Technical Work Ended: March 29, 2013

Date: July 22, 2013 Revision: 3

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and MicroAssembly Technologies, Inc.

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B. Project Scope

This was a collaborative effort between Lawrence Livermore National Security, LLC as manager and operator of Lawrence Livermore National Laboratory (LLNL) and MicroAssembly Technologies, Inc. (MAT) to develop spatial light modulators (SLM) based refocusing concentrators for telecom applications.

MAT submitted a Phase I Small Business Technology Transfer (STTR) proposal, listing LLNL as a subcontractor, to the United States Air Force and subsequently received a grant award under solicitation AF03T009. This joint collaboration was to develop a spatial light modulator (SLM) based refocusing concentrator systems for telecom and other applications. One industry expert from AT&T estimated that such a device could increase gain by about 16x, or add about 12 dB to the link budget.

The desired results of the Phase I effort was a successful feasibility demonstration of SLM based refocusing concentrators for telecom applications; and a study of system level architecture, micromirror array design and operating parameters for optimization.

Under Phase I, MAT was to design, fabricate, assemble and test its SLMs for refocusing concentrator systems for use in telecom and other applications. LLNL was to provide system level design input to MAT's design and prototyping effort. LLNL would also study system architecture, micromirror array design and operating parameters to optimize the gain of the refocusing concentrator system.

The duration of the Phase I effort was for nine months, and consisted of nine major tasks and the following two deliverables:

Two (2) mirror pixels and test data to be delivered to the US Air Force eight (8) months from the start of the project. (MAT)

System-level design report to be delivered to the US Air Force eight (8) months from the start of the project. (MAT and LLNL)

A no-cost time extension (NCTE) request was executed on October 12, 2004, extending the CRADA for an additional six months to allow enough time to receive Phase II funding and to amend the CRADA to add follow-on tasks, deliverables and funding.

Amendment One, executed on March 10, 2005, expanded the scope of the project adding Phase II tasks, deliverables, associated funding levels, and extended the term of the CRADA by an additional 24 months, to April 14, 2007.

In Phase II, MAT was to design, fabricate and assemble SLMs for refocusing concentrator systems for use in telecom and other applications, consisting of 8 tasks. LLNL was to (when SLMs were available for test from MAT) assist with the software and electronics interface with existing hardware. LLNL was to also test SLMs developed by MAT. This consisted of 2 tasks.

The Phase II deliverables were as follows:

1. Spatial light modulator prototype (piston only or tip-tilt-piston, up to 32x32). (MAT) Due at the end of Month 18
2. Test data of mirror actuation. (LLNL) Due at the end of Month 24
3. Final Report and Abstract due within thirty (30) days of completion or termination of the project, as required under Article XI of the CRADA. (LLNL/MAT) Due at the end of Month 24

Amendment Two, executed on December 12, 2006, deleted the last task of the project and replaced it with two new tasks, and extended the CRADA for an additional five months, to September 30, 2007. In Phase II LLNL would, in addition to the above, provide a gold sputtering target for MAT to coat the MEMS.

The Phase II deliverables were modified as follows:

1. Spatial light modulator prototype (piston only or tip-tilt-piston, up to 32x32). (MAT) Due at the end of Month 18
2. Delivery of gold sputtering target to MAT at the end of Month 16 (LLNL)
3. Test data of mirror actuation. (LLNL) Due at the end of Month 24
4. Return remaining gold sputtering target to LLNL. Due at the end of CRADA project. (MAT)
5. Final Report and Abstract due within thirty (30) days of completion or termination of the project, as required under Article XI of the CRADA. (LLNL/MAT)

NCTE #2 was executed on 9/20/07 to allow more time to produce the prototype needed to complete the final tasks and deliverables under the current Statement of Work. The CRADA was extended for twelve (12) months, to September 30, 2008.

NCTE #3 through NCTE #7 extended the CRADA for a total of fifty-seven (57) months to June 14, 2013. The purposes of the NCTE letters were to allowed enough time to complete tasks and deliverables associated with the CRADA Statement of Work.

MAT returned the remaining gold sputtering target to LLNL per the Property terms of the CRADA.

MAT was unable to develop a functional micromirror array SLM. MAT ran out of development funds before problems with the actuator design and assembly process could be resolved.

LLNL did not receive a spatial light modulator prototype from MAT and so was not able to complete the task of testing the mirror actuation.

C. Technical Accomplishments

The task of delivery of a gold sputtering target to MAT was completed at the end of Month 16 of Phase II. The target was returned to LLNL at the end of the CRADA. For the task of characterizing the MEMS mirror actuators, we developed two characterization setups. One that would measure the phase of the laser upon reflection from the MEMs and another that would measure the phase gradient. To measure the phase directly, a phase shifting interferometer was setup up, which could acquire four phase shifts simultaneously on the same CCD camera. The layout of this interferometer is shown in Fig 1 below. The waveplate array was manufactured by cutting commercially available polarizer arrays and then assembling into quadrants such that each subsequent quadrant has the polarization axis rotated 45 degrees relative to the previous quadrant. When a left-hand and right-hand circularly polarized beam pass through a polarizer at an angle α, the phase is advanced and retarded by the amount α, respectively. The overall phase difference between the two electric fields after passing through the polarizer is then 2α. By rotating the polarizer by α=45 degrees between the quadrants, the phase difference between the interfering electric fields is increased by 90 degrees. The four quadrants together can then form a conventional four-phase shift interferometer. $\tan(\phi)=(I_4-I_2)/(I_1-I_3)$, with phase steps in the references of the four channels of $0(I_1)$, $\pi/2(I_2)$, $\pi(I_3)$ and $3\pi/2(I_4)$, respectively.

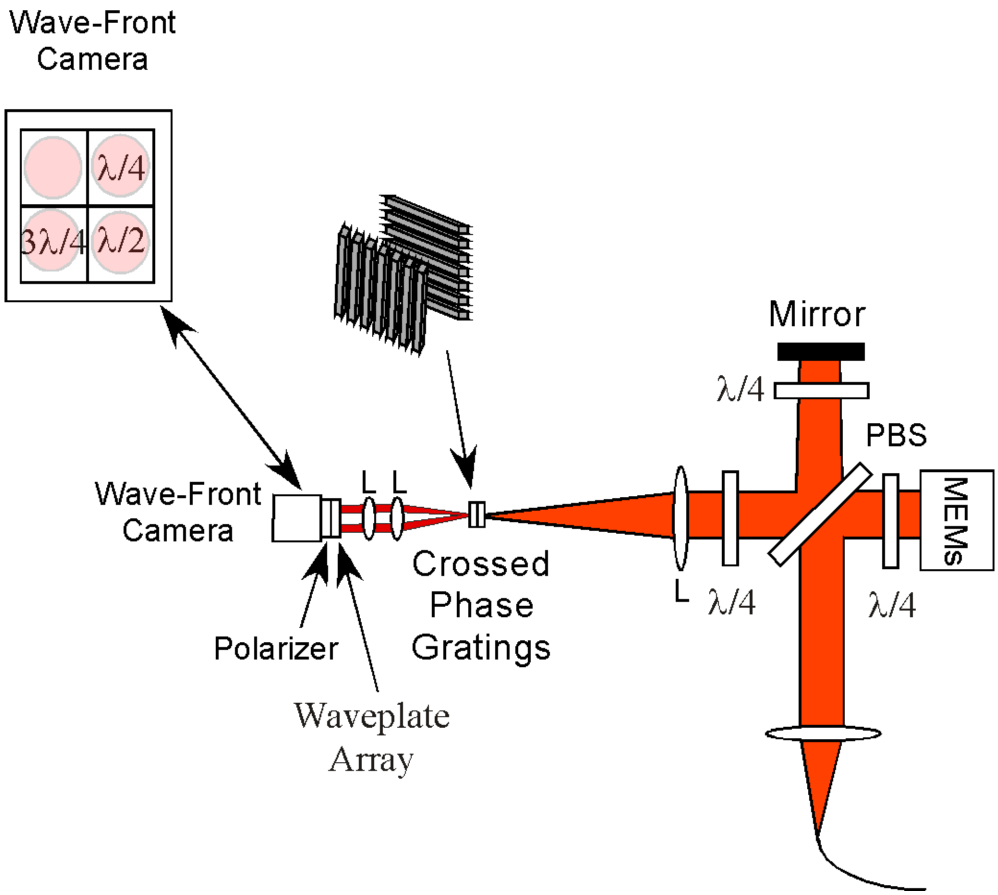

Figure 1 Two-dimensional phase shifting interferometer.

LLNL also developed a system that could measure the gradient in the phase of the laser upon reflection from the MEMs with a much higher spatial resolution than achievable with a Shack-Hartmann approach. This was accomplished through the use of two Wollaston prisms as detailed in Fig. 2 below. The first Wollaston prism was relay imaged onto the second Wollaston prism. The second Wollaston prism was rotated such that the separation between the ordinary and extraordinary refracted signals was orthogonal to those from the first Wollaston prism. A half waveplate or polarizer was placed between the first and second Wollaston prisms. Finally a polarizer was placed between the second Wollaston prism and the detector. That enabled interference between the four beams, the ordinary and extraordinary from each of the Wollaston prims. A sample interference pattern from the system is shown in Fig. 3.

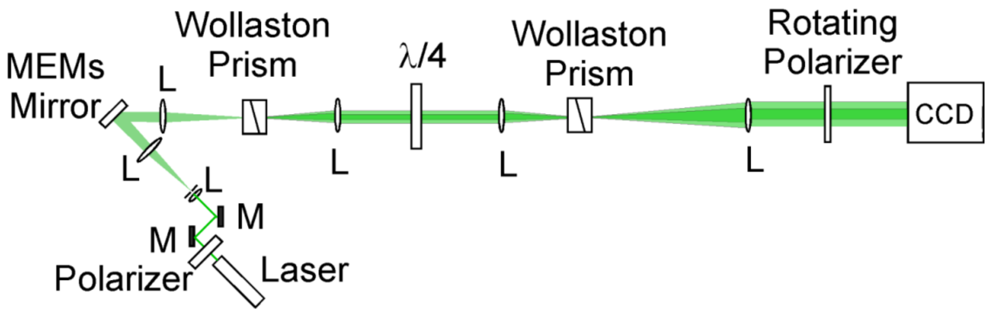

Figure 2 Two-dimensional shearing interferometer (Wollaston's at focus - imaging between planes)

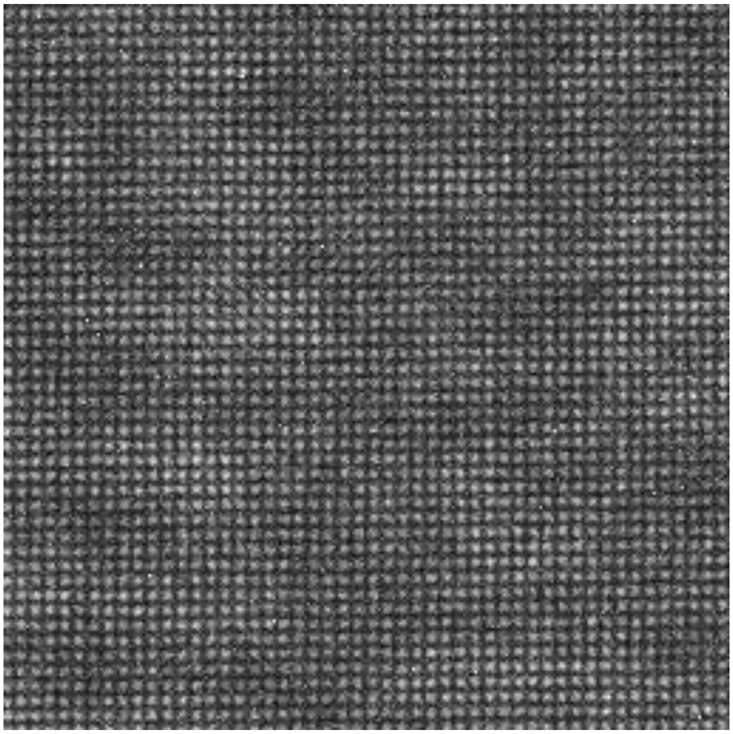

Figure 3 Sample interference pattern formed by the four interfering beams on the CCD camera for the Wollaston shearing interferometer.

MAT was able to fabricate and assemble transferred arrays of micromirrors with high apparent yield. However, actuator arrays did not appear to function correctly. Unresolved issues include determining the trouble with the assembled arrays. This may include but is not limited to debugging actuator design as well as unexpected consequences of the assembly paradigm. The characterization task of using the two systems developed for this CRADA was not completed because LLNL did not receive a prototype mirror from MAT.

D. Expected Economic Impact

If the SLM device was successfully developed, then applications include communications, laser machining and ophthalmic applications. Furthermore, a tip-tilt-piston device reduces the need for a fast steering mirror in many applications. This may simplify designs and enable smaller systems.

D.1 Specific Benefits

Benefits to DOE
DOE benefits from the MEMS-based spatial light modulators developed under this CRADA by enabling imaging, communications and targeting systems for astronomical, homeland defense and military applications. This collaboration may also lead to significant advances enabling low-cost adaptive optics that address critical telecom and defense applications such as free space optics communication systems for the telecom last mile problem; and imaging and targeting systems for defense and homeland defense use.

Benefits to Industry
The Participant benefits by potentially growing their business from the government sector into the commercial telecommunications and satellite industries with "free-space" optical networking. Free-space communications will help foster competition in these industry sectors. This CRADA benefits the U.S. Taxpayer because long distance carriers are seeking alternative telecommunications and satellite access to the end-customers.

Adaptive optics may also be useful in ophthalmic applications to measure and correct human vision and to enable the construction of molecular nano-structures via optical tweezers, which will improve the standard of living for all taxpayers.

E. Partner Contribution

MAT demonstrated the assembly of large arrays of microstructures including actuator arrays and mirror arrays. This included challenge assembly tasks that involved assembling fragile microstructures onto arrays of microstructures already assembled onto target wafers. Given the state of development, MAT does not intend to manufacture the micromirror arrays. MAT is investigating the use of the same transfer process for solar energy applications.

F. Documents/Reference List

Reports

A system level design report was incorporated within the Phase I Final Report entitled, "*MEMS Refocusing Concentrator for Free Space Optics*"; Principal Investigator: Michael Cohn; Report Period: September 30, 2003 to September 29, 2004.

Copyright Activity
None

Subject Inventions
None

Background Intellectual Property

LLNL disclosed the following Background Intellectual Property for this project:

U. S. Patent No. 6,577,428 - *Optical Electric-Field Pattern Generator*; Eddy A. Stappaerts; Issued 6/10/2003 (IL10721A)

U. S. Patent No. 6,934,475 - *Free-Space Optical Communications Using Holographic Conjugation*; Eddy A. Stappaerts; Issued 8/23/2005 (IL10722A)

MicroAssembly Technologies, Inc. has not expressed an interest in licensing the above LLNL Background Intellectual Property.

MicroAssembly Technologies, Inc. disclosed the following Background Intellectual Property for this project:

1. Designs for MEMS spatial light modulators (SLMs), light-weight mirrors for SLM and other optical devices, and actuators for SLMs and other devices. MicroAssembly has made prior commitments for some of its intellectual property. However, LLNL will be able to use MicroAssembly's Background Intellectual Property identified in this CRADA solely in performance of research in the Statement of Work for this CRADA.

2. Fabrication, manufacturing, integration and packaging technologies for MEMS SLMs, light-weight mirrors for SLMs and other optical devices, and actuators for SLM and other devices. MicroAssembly has made prior commitments for some of its intellectual property. However, LLNL will be able to use MicroAssembly's Background Intellectual Property identified in this CRADA solely in performance of research in the Statement of Work for this CRADA.

3. Bump bonding technologies for integrating different technologies, such as MEMS, CMOS and HV ASIC for assembly and fabrication of MEMS SLMs and other devices. MicroAssembly has made prior commitments for some of its intellectual property.

G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

[signature] 7/29/13
Michael Cohn, Chief Technology Officer — Date
MicroAssembly Technologies, Inc.

Kevin Baker 8/8/13
Kevin L. Baker, LLNL Principal Investigator — Date
Lawrence Livermore National Laboratory

[signature] 26 August 2013
Richard A. Rankin, Director — Date
Industrial Partnerships
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

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Final Abstract (Attachment I)
CRADA No. TC02073.0
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LLNL also developed a system that could measure the gradient in the phase of the laser upon reflection from the MEMs with a much higher spatial resolution than achievable with a Shack-Hartmann approach.

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Adaptive optics may also be useful in ophthalmic applications to measure and correct human vision and to enable the construction of molecular nano-structures via optical tweezers, which will improve the standard of living for all taxpayers.

E. Project Dates

January 14, 2004 through March 29, 2013