REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-02-2010	Final	10-12-2007 - 01-02-2010

4. TITLE AND SUBTITLE
Low Power MEMS Retroreflectors for Optical Communication

5a. CONTRACT NUMBER
W911NF-08-C-0006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven Cornelissen
Mark Horenstein
Jason Stewart

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston Micromachines Corporation
30 Spinelli Place
Cambridge, MA 02138

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army RDECOM ACQ CTR
4300 S. Miami Blvd
Durham, NC 27703

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
1. Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Report developed under STTR contract W911NF-08-C-0006. In this Army Phase II STTR program, the BU and BMC project teams successfully designed, developed and tested a new low-power, light-weight and low-cost modulating retroreflector (MRR) system for free-space covert optical communication and remote sensor interrogation. The central component of the prototype is a MEMS modulator mirror, which is physically similar to a very low modulation reflective diffraction grating that has actively controlled groove depth and can operate at frequencies up to 1MHz. One facet of a hollow corner cube retroreflector consists of the MEMS mirror, which provides intensity modulation of a reflected interrogating beam by switching from an unpowered flat mirror state to a powered diffractive state. The system is optimized for performance at 1550nm and has a field of view of 60 degrees. For covert operation it uses “wake-up” circuitry to control a low-power shutter that remains closed between data transfers. The system’s compact driver electronics employs power scavenging and resonant properties for minimal power consumption and extended autonomous operational life. The MRR prototype system developed in this program was capable of providing 180kbps data rates

15. SUBJECT TERMS
STTR Report

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Steven Cornelissen
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	16	617-868-4178

Reset

Low Power MEMS Retroreflectors for Optical Communication

Contract#: W911NF-08-C-006

Final Report

February 1, 2010

Boston Micromachines Corporation
30 Spinelli Place
Cambridge, MA 02139

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1 SUMMARY

In this Army Phase II STTR program, the BU and BMC project teams successfully designed, developed and tested a new low-power, light-weight and low-cost modulating retroreflector (MRR) system for free-space covert optical communication and remote sensor interrogation. The central component of the prototype is a MEMS modulator mirror, which is physically similar to a very low modulation reflective diffraction grating that has actively controlled groove depth and can operate at frequencies up to 1MHz. One facet of a hollow corner cube retroreflector consists of the MEMS mirror, which provides intensity modulation of a reflected interrogating beam by switching from an unpowered flat mirror state to a powered diffractive state. The system is optimized for performance at 1550nm and has a field of view of 60 degrees. For covert operation it uses "wake-up" circuitry to control a low-power shutter that remains closed between data transfers. The system's compact driver electronics employs power scavenging and resonant properties for minimal power consumption and extended autonomous operational life. The MRR prototype system developed in this program was capable of providing 180kbps data rates using a single 9V battery for a 24-hour time period. Communication links were demonstrated at distances up to 2km using the NovaSol Inc. CI4 interrogation system, which uses a 1550nm CW laser source and results suggest communication links up to 5km are possible with this interrogator and MRR system setup.

2 INTRODUCTION

Optical communication has emerged as a critical need for military operations in situations where conventional radio frequency (RF) channels are disrupted or unavailable for use, such as when jamming equipment is employed to block RF trigger signals sent to improvised explosive devices (IEDs). A high-bandwidth point-to-point optical-link provides an alternative, robust and secure means of voice and data communication in this setting. In several circumstances, asymmetric communication with a remotely located node is needed where conventional free space optical communication hardware cannot be supported due to its size and power consumption, such as beam pointing and tracking hardware, or high-power laser sources. A prominent solution to this problem involves the use of a modulating retroreflector (MRR) which is capable of passively returning light from an interrogating laser source via retro-reflection while simultaneously modulating its intensity for communication.

Numerous MRR systems have been developed in recent years that use a variety of retroreflector optical designs and intensity modulation schemes. In general, these systems share a common goal of improving data rates, covertness, immunity from RF jamming, field of view, range, modulation contrast, and compatibility with a wide band of interrogator wavelengths. They also aim to have reduced power consumption, size, weight and cost. Several new MRR technologies were developed in the DARPA Dynamic Optical Tags (DOTs) program that used multiple quantum wells (MQW), optical micro-electro-mechanical systems (MEMS) and electro-optic modulators. The use of multiple quantum wells as electro-absorbers or shutters to modulated retro-reflected light have been largely successful satisfying many MRR application needs. These devices offer bandwidths of tens of MHz and are very compact. However, the MQW approach is limited to a narrow range of interrogation laser wavelengths and the system is relatively complex to manufacture, increasing its cost. A number of other groups have developed MRRs that use a combination of MEMS modulator technology and corner cubes or cat's eye retroreflectors. While these systems have not yet achieved the data rates established by MQW technology, they do promise a low-cost, low-power solution capable of being used with a wide range of interrogator laser wavelengths.

The **goal** of this Phase II program was to develop a compact, portable, low power, and light weight modulated retro-reflecting node for covert communication and remote sensor interrogation and to demonstrate its functionality. The three specific aims of this work were:

1. Develop a MEMS modulator capable of operation at 250 kHz
2. Develop an MRR that attenuates the intensity of the interrogating laser when unpowered and reflects when in its powered state
3. Develop compact drive electronics capable of:
    a. Driving the MEMS modulator at frequencies between 0.1 Hz and 250 kHz,

b. Transferring both audio and stored digital data, such as personnel/asset ID, via the retro-reflected beam,

c. Residing in a normal "sleep" state and powering itself upon illumination by the interrogator,

The enabling component of the MRR system, developed in this project, is a MEMS modulator mirror that is physically similar to a reflective diffraction grating with controllable groove depth. It is mounted as one facet of a hollow corner cube retroreflector and provides far-field intensity modulation of a reflected interrogating beam by switching between an unpowered flat mirror state to a powered diffractive state, as shown in Figure 1. With sufficient separation between the interrogator and MRR only the 0^{th} order of the far-field diffraction pattern is returned to the interrogator. A change in the modulator groove depth directly influences the diffraction efficiency of the 0th order, providing a method to modulate the returned intensity of the interrogation source.

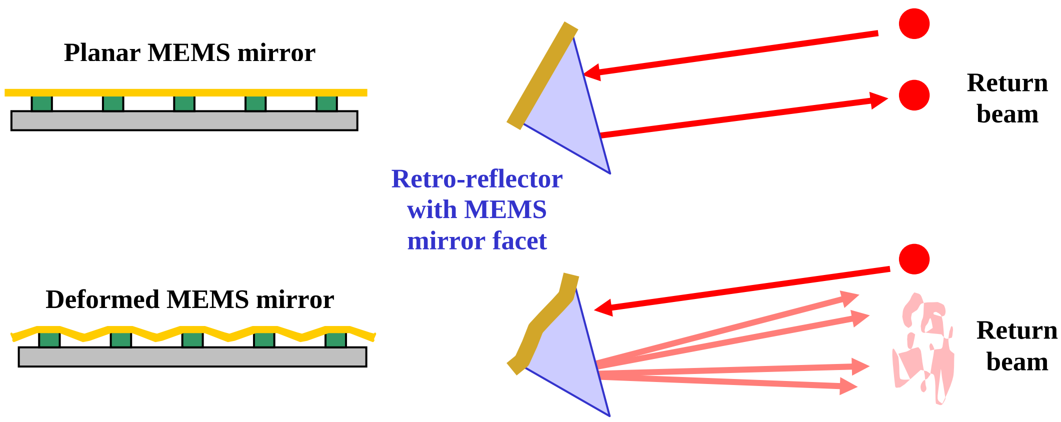

Figure 1: Optical communication link using MEMS modulator and hollow corner cube retroreflector.

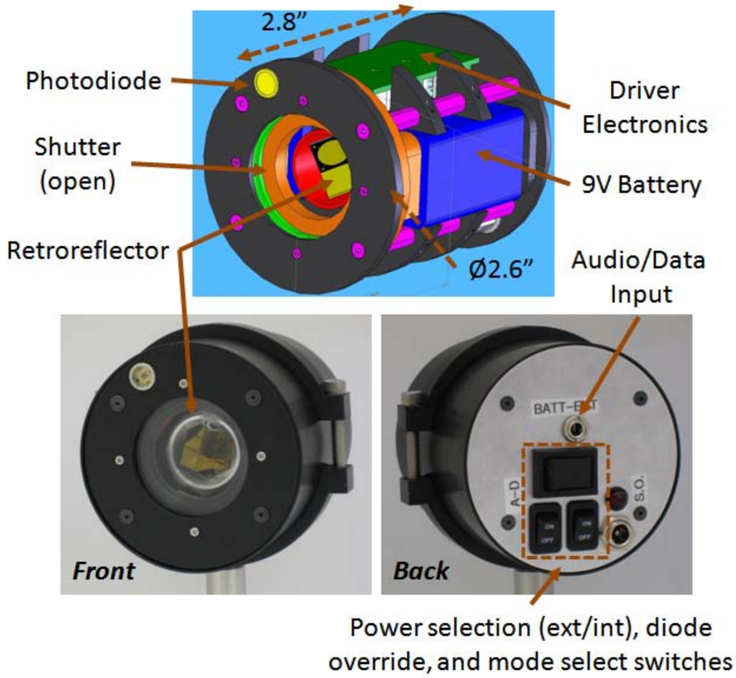

Figure 2: Fully assembled and functional MRR prototype.

The compact, low-power high-voltage driver design used to control the modulator using a single 9V battery was also developed in the Phase II effort. The driver amplifier pairs the inherent capacitance of the modulator with an inductor to produce resonant voltage pulses of approximately 120V at frame rates exceeding 100kHz. This inductor-capacitor (LC) boost circuit is also capable of recycling power, providing continuous operation lifetimes exceeding 24hours, and intermittent interrogation lifetimes on the order of 6 months. Images of the MRR prototype developed in this work can be seen in Figure 2.

This final program report is divided into three sections. In the first section we review the MRR optical design, including a discussion of the fabrication process for the BMC MEMS modulator, as well as recent optical and electromechanical characterization results. The new LC-boost driver is presented in the second section, and the report concludes with the results of recent field tests for the MRR prototype.

3 Modulated Retro-Reflector (MRR) Optical Design

3.1 Hollow corner cube retroreflector

The central component of the MRR system is a hollow corner cube retroreflector that modulates and passively returns the interrogating laser beam to its source. Two of the three mirror facets of the retroreflector consist of 500µm thick gold-coated silicon die measuring 11mm on a side. The third mirror facet is a BMC MEMS modulator, which is fabricated on a silicon substrate of similar dimensions and has a gold-coated active aperture that measures 9mm in diameter. The three die are aligned and bonded using a proprietary process to produce the retroreflector (Figure 3, left). Eight retroreflectors were assembled as part of this work, each having parallelism or beam deviation better than 30arcsec. The retroreflector selected for the MRR prototype has 13arsec parallelism. The retroreflector is located on the axis of the cylindrical MRR housing behind a protective window and bi-stable shutter that is closed when the system is inactive to provide covertness. The system uses an externally mounted infrared (IR) photodiode to sense when it is being interrogated, triggering it to open the shutter and begin data transfer. The aperture of the MRR housing does not obstruct the incident or reflected interrogator beam, providing that the system field of view (FOV) is limited only by the corner cube geometry, which was evaluated to be approximately 60° (full-width-half-max) as seen in Figure 3 (right) well in access of the 60° FOV target performance.

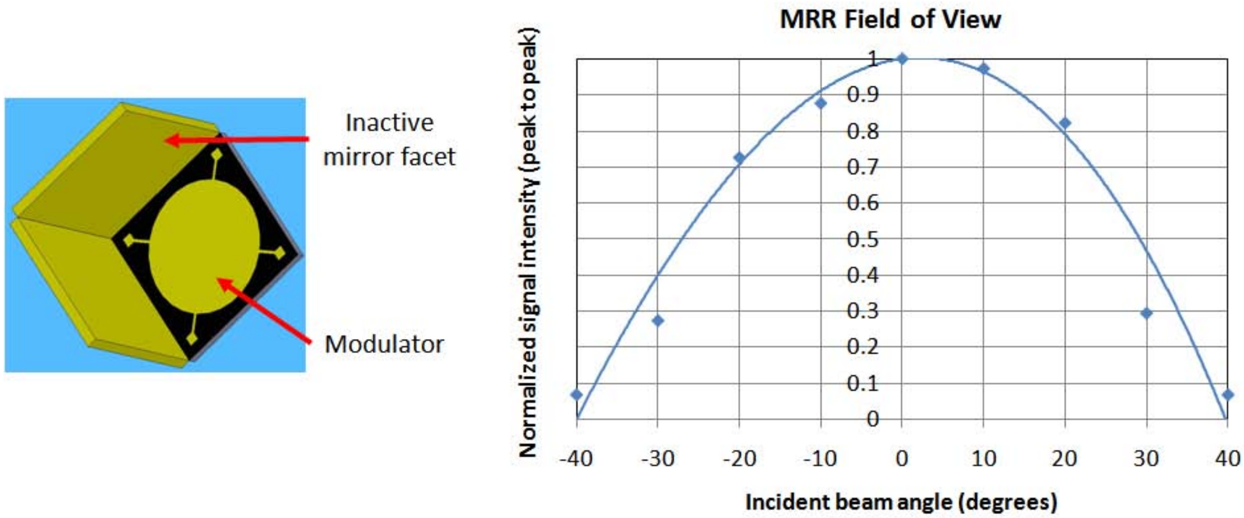

Figure 3: Illustration of hollow corner cube retroreflector using the BMC MEMS modulator (left). Measured retroreflector field of view (right).

3.2 Lens-based retroreflector design study

A comprehensive optical modeling effort that investigated lens-based solutions for the retroreflector optics was also completed in this work. A lens based solution is desirable as it could also easily be adapted into a hermetic packaging design, which was also evaluated in this work using wedged windows. The retro modeling effort explored two cats eye retroreflector (CERR) optical designs, which also involved an evaluation of modulator integration. The first CERR design involved an array of graded index (GRIN) lenses, and the second design involved a conventional approach that relies on an image plane at a mirror with optical power. The principal task for the modeling effort was to compare the performance of these designs to that of the hollow corner cube retroreflectors (CCR). Comparisons for these three retroreflector designs focused on performance characteristics, such as clear aperture, divergence, spots size, and field of view. Most importantly however was an evaluation of system integration, i.e. maintaining weight and compactness specifications.

Both CERR designs were evaluated in the lab and found to be successful retroreflectors when the modulator was in the flat or off state. However, neither approach performed as well as the hollow CCR design. The GRIN lens array CERR design was not able to accommodate the diffractive nature of the modulator, in that the spot size of the GRIN lenses was too small and did not illuminate enough modulator actuators (diffraction grating grooves) to modulate the incident signal. On the other hand, the conventional lens-based CERR design was a viable solution and capable of signal modulation, however has a reduced field of view (about +/- 10degrees) and significant beam distortion in the reflected field. The lens based solution is also much larger than that provided by the CCR. For these reasons, the CCR design was selected for MRR integration.

3.3 Modulator design and fabrication

The BMC MEMS modulator technology behaves similarly to a reflective diffraction grating. The modulator is optically flat in its “off” state and a diffraction grating in its “on” state, thereby redirecting most of the reflected light out of the specular reflection path. The grating groove depth is controlled through electrostatic actuation of the mirror surface, which influences the diffraction efficiency of the 0^{th} diffraction order (or on-axis far-field intensity). When the modulator is fully energized, its groove depth to pitch ratio is less than about 5%, providing behavior similar to that of a very low modulation grating. To a first order, this family of gratings is insensitive to polarization, conical mounting configurations and can be modeled using scalar diffraction theory. A schematic illustrating the modulator design can be seen in Figure 4 (left), which demonstrates how the mirror surface is deformed via electrostatic actuation. A magnified surface profile measurement of the deflected modulator surface can be seen in Figure 4 (right).

The modulator is fabricated on an optically-flat, electrically-conductive silicon substrate that also functions as one actuator electrode. The other electrode is the mirror surface which is fabricated using MEMS surface micromachining. The fabrication process begins with the deposition of a non-conductive silicon dioxide film on a silicon substrate. This material functions as both the sacrificial layer that sets the gap between the electrode and the actuator membrane, as well as structural supports or anchors for the mirror layer. A non-conductive silicon-nitride film is then deposited on top of the silicon dioxide layer to create the flexible upper membrane of the electrostatic actuator. The nitride layer is patterned with oxide etch release holes, which determines the grating or actuator geometry. The oxide layer is then partially released using a HF acid wet etch to form the actuator gap. After release the devices are gold coated using electron-beam evaporation, creating the second actuator electrode and a highly reflective mirror surface particularly in the IR. This microfabrication process has the sole purpose of producing modulator technology in a cost-effective manner using commercial semiconductor batch processing techniques. Each fabrication step is based on widely available, standard semiconductor fabrication process, providing high-volume production capability.

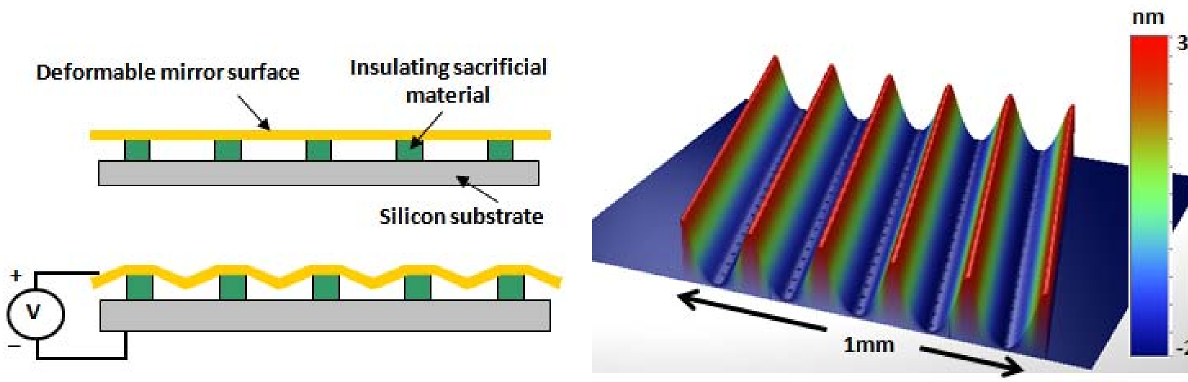

Figure 4: Profile of MEMS Modulator architecture. In its “off” state, the mirror surface is flat (top left), and in its “on” state (bottom left and right) the mirror surface behaves as a diffraction grating. The image on the right is a surface profile measurement made using a Wyko NT9100 interference microscope.

With the application of a voltage (V) between the modulator reflective surface and the device substrate, the mirror actuators experience deflection. During electrostatic actuation, only the released portion of the mirror surface experiences deflection, while the area above the oxide supports remain flat. The grating profile of the deflected modulator is therefore similar to that of a symmetric scribed or ruled grating. The thicknesses of the oxide, nitride and gold layers determine the profile shape of the deflected actuator. The fabrication process developed in this work produced devices capable of producing a maximum modulator groove depth (or stroke) on the order of 1µm and a minimum pitch on the order of 50µm. The device developed for this program has a 200µm pitch, 185µm span and mechanical stroke (groove depth) of up to 850nm. Electrostatic actuation is an effective method for providing hysteresis free motion of the modulator mirror surface with nanometer-level precision. These actuators are capacitive in nature and consume very little power. Their capacitance is on the order of 100pF, which is advantageous in the design of the low-power high voltage driver electronics discussed below.

3.4 Modulator optical and electromechanical characterization

Prior to assembling the modulator die into hollow corner cube retroreflectors, their optical and electromechanical behavior are first evaluated using a Wyko NT9100 surface profiling interference microscope and an optical test setup that simulates the modulator’s configuration in the MRR system. Both static and dynamic performance is evaluated. The characterization setup, illustrated in Figure 5, projects the far-field intensity pattern of the modulator onto a high-speed photo detector using conventional optics. The photo detector uses an adjustable iris such that only light from the 0th diffraction order is incident on the detector active area. This provides the ability to measure the diffraction efficiency for this order as the modulator electrostatic actuators deflect, or in other words as the grating groove depth increases. The setup uses either a 633nm or 1550nm laser source that is expanded, collimated (L1 and L2) and stopped to the active aperture of the modulator. The angle of incidence (AOI) of the beam on the modulator surface is 45°, similar to its mounting angle in the retroreflector. Lenses L3 and L4 are used to project the modulator far-field diffraction pattern onto the photo detector, which has a 2.1MHz bandwidth and can be exchanged between InGaAs and Si depending on the illumination wavelength used. The axial position of L4 can be translated to accommodate for the change in focus for the two different wavelengths. For ease of use, modulators are typically packaged in ceramic 144-pin grid arrays (PGA) prior to testing, which are used for other BMC deformable mirror (DM) technology (Figure 6 – left). Voltage is applied to the modulator via four wire bond-PGA connections to the reflective gold layer. The silicon substrate is grounded to the PGA cavity floor using silver epoxy.

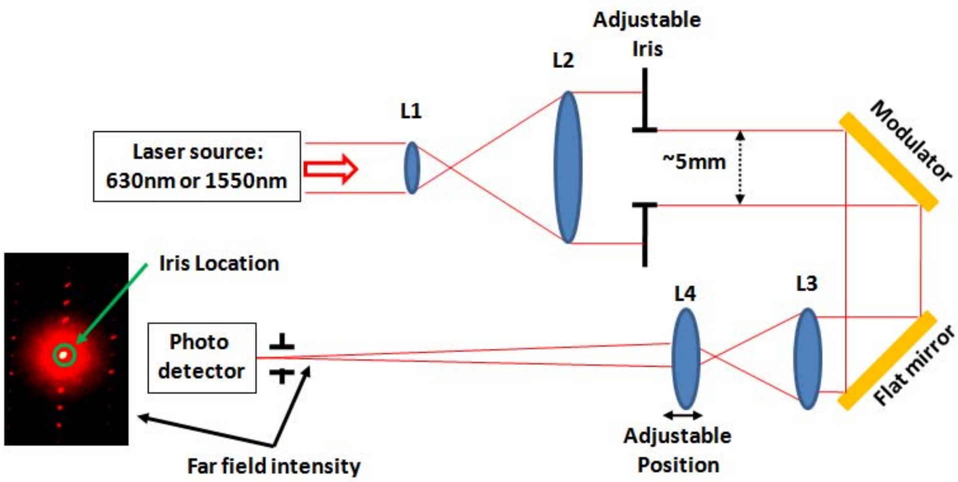

Figure 5: Modulator optical characterization system.

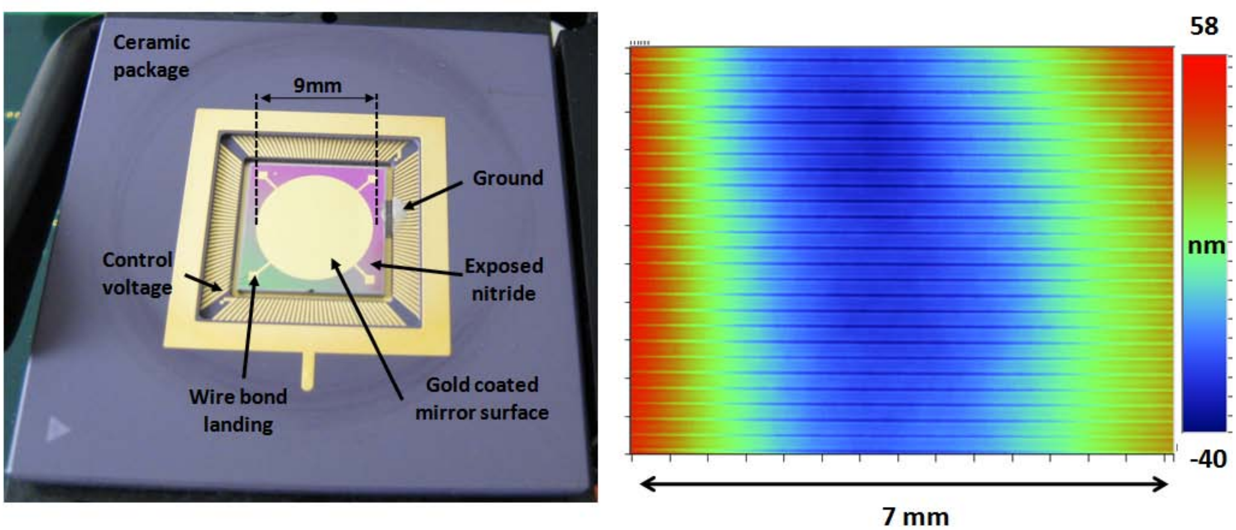

Figure 6: Modulator packaged in ceramic PGA for testing purposes (left). Typical modulator surface figure at the center of the active aperture, measured using a Wyko surface profiling interference microscope (right). The surface flatness is 21nm RMS and its radius of curvature is 120m.

The optical and electromechanical performance of a 200µm pitch modulator with 185µm span actuators can be seen in Figure 7 for 1550nm illumination. The diffraction efficiency of the 0th order is reported in terms of modulation contrast, which is calculated using the Michelson formula: (PDV_{max} – $PDV_{current}$)/(PDV_{max} + PDV_{min}), where PDV is the measured photo detector voltage. The modulation contrast versus applied voltage is plotted on the primary plot axis and the deflection versus applied voltage is shown on the secondary axis. Here it is shown that the modulator is capable of achieving slightly greater than 98% modulation contrast of 1550nm illumination at 45 degree AOI at an applied voltage of approximately 110V, which corresponds to an actuator deflection of about 800nm. The dynamic performance of the modulator at atmospheric pressure can be seen in Figure 8. The modulation contrast results shown correspond to the modulator response to an 8kHz square wave of 110V amplitude. Here it is shown that the device has an over damped response, achieving 98% contrast in about 40µs and 50% contrast in about 7µs.

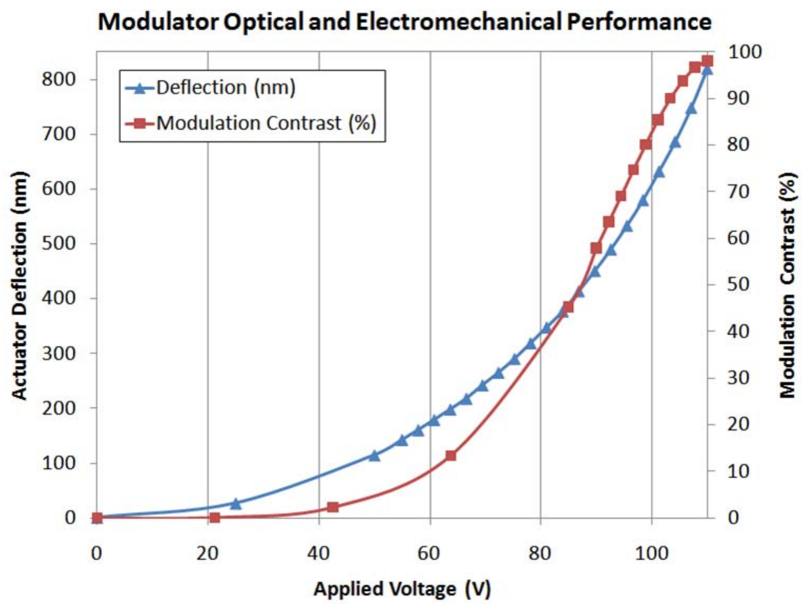

Figure 7: Actuator deflection and modulation contrast behavior for a 200µm pitch modulator with an 185µm span.

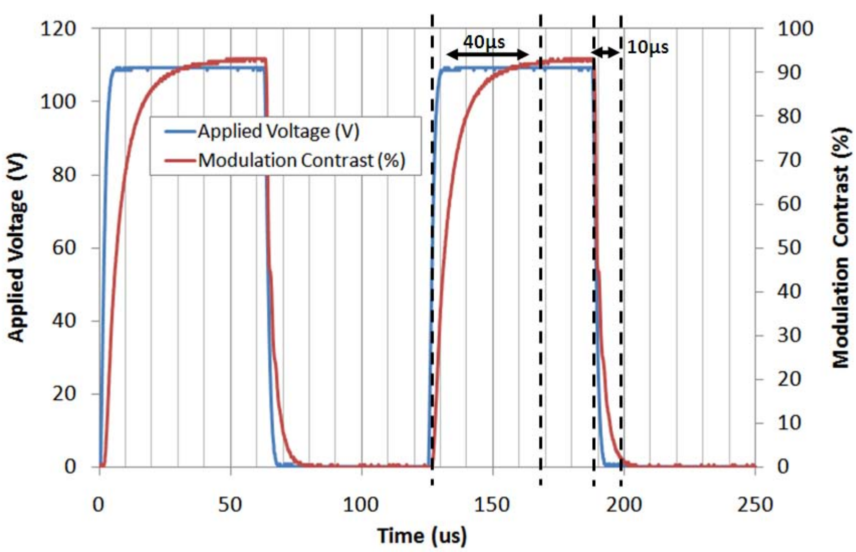

Figure 8: Dynamic response of the 200um span modulator to a 0 to 110V, 8kHz square wave, as seen by the photo detector in the optical characterization system.

4 **MRR ELECTRONICS**

4.1 MEMS modulator driver design

The MEMS modulator mirror, with its two separated conductors, can be regarded as a capacitor. While this capacitance is an inherent characteristic of the MEMS modulator mirror, it is fortuitous because this capacitance can be utilized in combination with an inductor to create a resonant inductor-capacitor (LC) boost circuit. This resonance allows the use of modestly sized 9 V batteries to create periodic voltages over 100V, necessary to create detectable deflections, without utilizing transformers or DC-DC converters. In addition the LC boost circuit operates at frequencies in the 100's of kHz while recycling the energy stored on the capacitive load, making the circuit inherently low-power. The LC boost circuit is an ideal drive mechanism to create a portable, efficient, and battery operated electronic controller capable of driving the MEMS mirror at high speeds.

In Figure 9, the schematic of the LC boost is shown as well as the LC boost circuit's functionality for transmitting a one-bit. The three phases for a single cycle are the pre-charge (PC), blip generation (BLIP), followed by a return energy phase (RET).

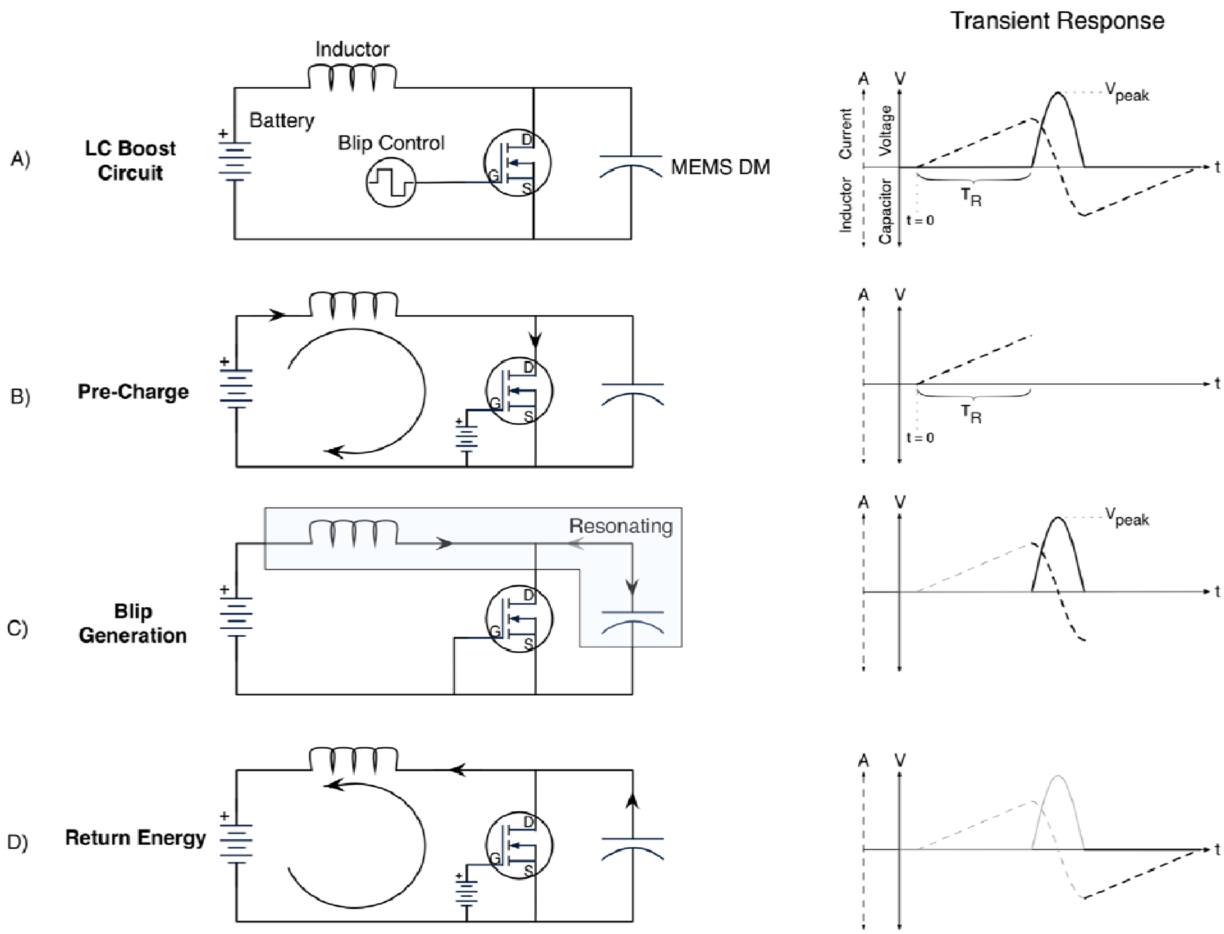

Figure 9: Circuit and transient response of the LC boost circuit. A) The LC boost circuit with a battery, inductor, N-channel MOSFET, and MEMS deformable mirror. B) During the pre-charge phase the current ramps up in the inductor. C) Blip generation occurs when the MOSFET gate voltage is lowered, resulting in half a sinusoid wave, peaking when the current through the inductor is zero. D) The final phase returns the current into the battery.

PC: The initial pre-charge phase occurs when the N-channel MOSFET's gate voltage is brought above threshold, allowing current to flow through the inductor. Since the battery's voltage is constant, the current through the inductor ramps up linearly according to Equation 1, where V is the battery voltage, L is the inductance, $i(t)$ is the instantaneous current and t is the time after the gate voltage is raised.

$$\frac{di}{dt} = \frac{V_{DC}}{L} \rightarrow i(t) = \frac{V_{DC} \times t}{L} \qquad (1)$$

The inductor stores energy, E_p, in the magnetic field, specified by Equation 2. V_{DC} is the battery's voltage, I is the instantaneous current at the end of the pre-charge phase of duration T_p. The amount of energy stored in the inductor can be adjusted by changing the charge time, T_p, as long as the inductor core does not saturate.

$$E_p = \frac{1}{2}LI^2 = \frac{1}{2}\frac{L(V_{DC} \times T_p)}{L} \qquad (2)$$

BLIP: When the transistor's gate is brought low, the transistor switch is opened and the inductor feeds current to, and resonates with, the capacitive load. The resonant frequency, f, is given by Equation 3, where C is the load capacitance, primarily composed of the MEMS mirror capacitance.

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (3)$$

The blip stage is composed of a half-cycle of a sinusoid at frequency f. This half-cycle peak occurs when the inductor transfers the energy stored during the PC phase, into the capacitor. The capacitor's energy, E_C, follows Equation 4, where V_{DM} is the voltage across the capacitive load C.

$$E_c = \frac{1}{2}CV_{DM}^2 \qquad (4)$$

Since the law of energy conservation is obeyed, Equation 4 is equal to Equation 3. This results in a maximum, or peak voltage, V_{peak}, coinciding when the current through the inductor is equal to zero, as shown in Equation 5. At this point the circuit begins resonating and the energy that is stored in the capacitor as an electric potential flows back into the battery through a negative current flow through the inductor.

$$V_{peak} = \frac{V_{DC} \times T_R}{\sqrt{LC}} \qquad (5)$$

The peak voltage is applied to the deformable mirror, resulting in mirror deformation and reduction in reflectivity. Examining Equation 5, the peak voltage can be controlled by changing the charge time, T_R, allowing one to increase modulation contrast by increasing MEMS mirror deflection through the peak voltage.

RET: After the circuit completes one half-cycle of resonance, the capacitor voltage swings back to zero, and the MOS switch is again closed. The current through the inductor now flows into to the battery, thus returning whatever portion of the previously stored energy has not succumbed to inductor-core or resistive system losses. If the switch timing is correctly chosen, power loss occurs only from the parasitic resistances plus the inductor core loss. This action results in a circuit that operates at high efficiency.

The LC boost circuit is used to transmit digital ones through the PC, BLIP, and RET phases. Zero bits are transmitted by the absence of these phases. The BLIP stage is a smaller portion of the data cycle and therefore requires conversion of modulated laser reflections into data bits through the use of a series of electronic components on the interrogator side.

4.2 MRR system electronics

In addition to the LC boost circuit used to drive the MEMS mirror, the retroreflector is equipped with additional electronics to control the LC boost in a low-power and controllable way and "wake-up" circuitry to provide long-term operations that can help mask unwanted detection. The current system, as shown in Figure 10, can transmit audio information or used as a modem to transmit digital data over free-space.

The central control device used is Texas Instruments' MSP430F2012 (MSP430), a 16-bit microcontroller capable of ultra low-power operation, 10-bit analog-to-digital (ADC) operations, and vital hardware timers. The hardware timers of the MSP430 provide the precise timing necessary to operate the LC boost circuit. The MSP430, in conjunction with an infrared (IR) photodetector, can enter a low-power sleep mode where only an interrogator's IR pulse will awaken the system to initiate communications. The sleep mode enables long-term operations in the field by shutting off all unnecessary peripherals until a "wake-up" pulse is received. Audio is filtered to prevent aliasing before digitizing with the built-in ADC. The filter is a simple passive band-pass filter to reduce power requirements. Since the MEMS mirror's natural state is reflecting the retroreflector is easily detectable. A digitally controlled bi-stable shutter protects the mirror when the retroreflector is in sleep mode. To interface with the shutter, the MSP430 uses an H-bridge to provide a positive supply voltage pulse to open the shutter, and a negative supply voltage pulse to close it. Finally a high-speed and low-power comparator is used as a voltage level-shifter to control the N-channel MOSFET. The higher voltage is necessary to raise the gate voltage above the threshold voltage of the transistor- something the MSP430 is incapable of doing without external components.

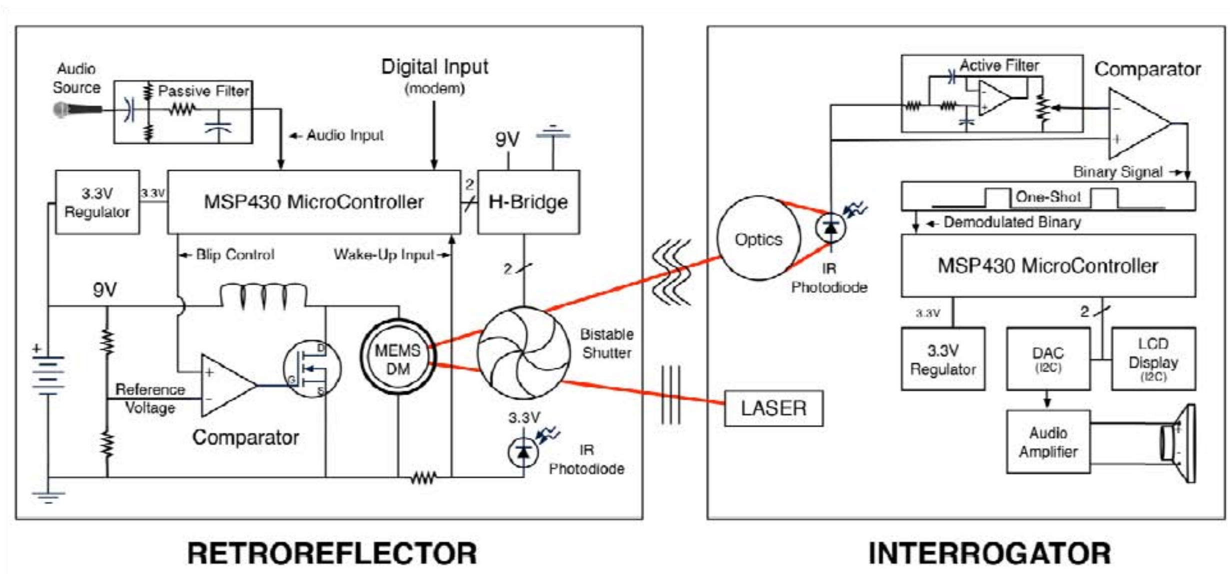

Figure 10: Retroreflector and interrogator system electronics.

4.3 Interrogator electronics for MRR demonstration

Receiving the reflected modulated light and demodulating it into useful data is performed by the interrogator electronics. This is accomplished using the system presented in Figure 10. An IR laser illuminates the modulating MEMS mirror, and the collected light is focused onto an IR photodiode. The output of the photodiode is used as the positive input of a comparator, where the negative input comes from a second-order low-pass active filter with a 1 kHz corner frequency. The filter has an adjustable output attenuation which is used to set a dynamic reference point for the high-speed comparator. This allows the comparator to respond to only high-speed changes, such as the MEMS modulated response, and adapt to slow-speed atmospheric turbulence or ambient effects. The comparator creates digital pulses that coincide with the modulated signals. Since the MEMS mirror can have an under-damped mechanical response and possibly create multiple digital pulses over one cycle, the output of the comparator is fed into a non-resettable one-shot that recovers the data for one period so that the interrogator MSP430 can correctly decode multiple short pulses over one cycle as a single bit. The MSP430 can output the decoded packets either as audio by using a digital-to-analog (DAC) converter and an adjacent amplifier that can output audio to a speaker or headphones. Digital data can be displayed on the built-in LCD display or used in another system. A standard MEMS data packet, as shown in Figure 11, is used for all communication between the retroreflector and the interrogator. The data is transmitted in packet form so that it can be sent asynchronously. This allows sudden interruptions in data transmission and also allows the system to begin transmission at any time. The data packet consists of a start bit that is used to align the beginning of a packet. The second bit determines whether the data is encoded as 10-bit audio or 8-bit binary data.

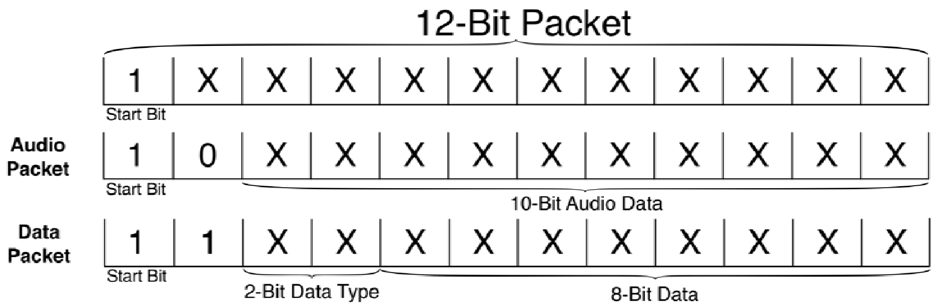

Figure 11: MEMS data packet format. The start bit is used to align the 12-bit word to decode the packets as they arrive, since they can be transmitted asynchronously. The second bit indicates whether a 10-bit audio packet (0) is the payload, or whether the data is digital in nature (1). If the data is digital, the next two bits determine the type. The two current types are signaling information or 8-bit modem communication. The remaining two states are reserved for future use.

5 MRR PROTOTYPE TEST RESULTS

5.1 Lab Tests

Using an optical bench interrogator design with a 20mW, 1550nm CW laser source, a successful test of the MRR prototype system was performed at a distance of 77 meters indoors, or 154 meters round trip. Audio was transmitted at about half the maximum data rate due to limitations imposed by detecting and decoding the data on the interrogator board's MSP430. The data rate achieved was approximately 180kbps (Figure 12). A more powerful processor could utilize the maximum bandwidth available in the system, although modulation contrast begins to fall off due to the dynamic response of the MEMS mirror. With a 9V supply, the LC-boost driver voltage pulse for the prototype MRR system has peak amplitude of approximately 100V and duration of about 1μs, which is capable of modulating the contrast of the retroreflected signal by about 12% at 1550nm. With a 12V battery (max allowable by driver electronics), the peak amplitude of the driver voltage pulse is approximately 120V, which provides about 15% modulation contrast. Figure 12 illustrates a single packet of data being modulated by the retroreflector and captured with an IR photodiode. The modulated signal is then processed on the interrogator board to correctly digitize and interpret the binary data. A series of packets is shown in Figure 13 and then the 10-bit audio data is converted with a DAC to the appropriate signal value. Figure 14 contains data for the drain response of 9 V Energizer batteries with various loads. The battery data for the retroreflector was recorded with only one battery, but the system can accommodate two batteries in parallel to increase the lifetime of the system. Using a single 9V battery, 24 hour continuous MRR audio transmission operation was achieved. Extended lifetime tests are planned for intermittent MRR operation.

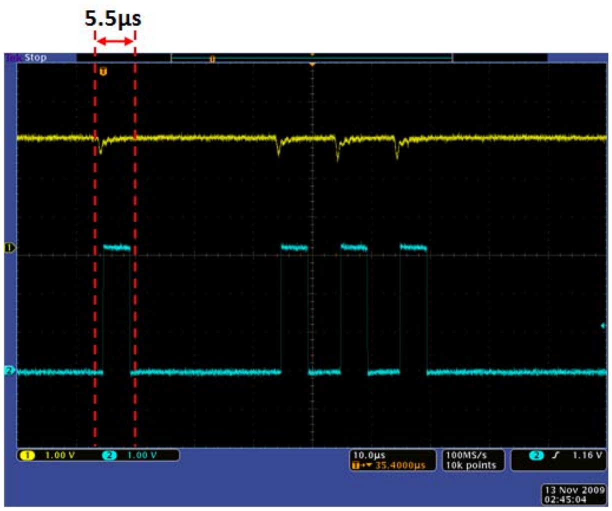

Figure 12: A captured packet on the interrogator. The top line is the photodiode signal that has been DC coupled, with 1V per division. The bottom line is the digital signal, with 1.0 V per division, after the comparator and one-shot have sucessfully demodulated the photodiode's response. The data was captured on a Tektronix MSO4032 oscilloscope.

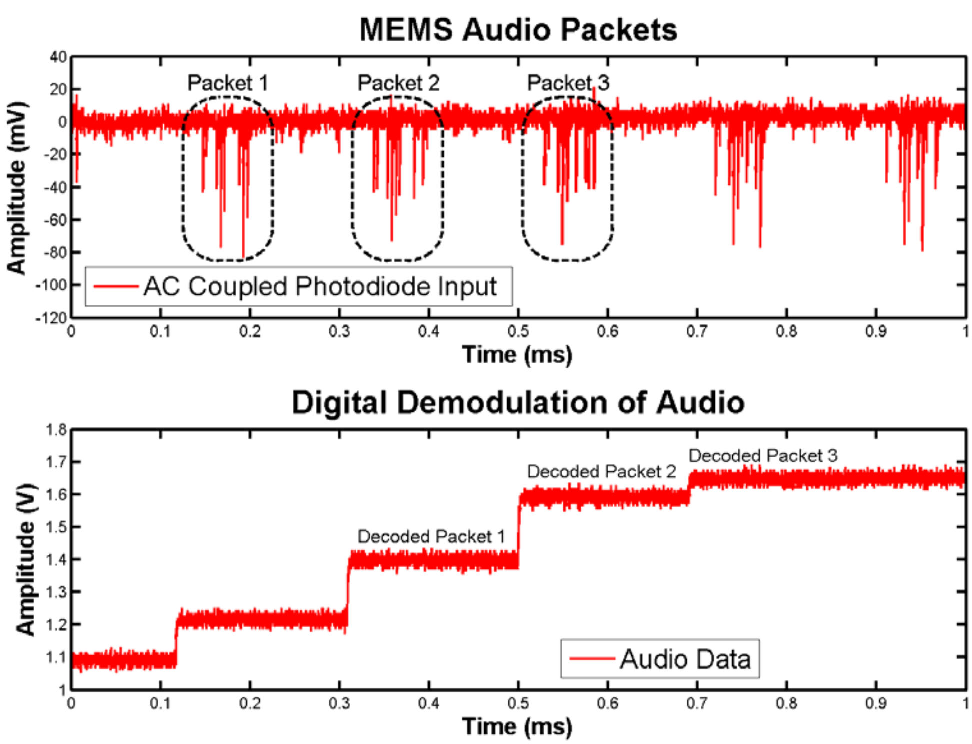

Figure 13: MEMS audio data decoding a series of packets. The packets are delayed to give the MSP430 on the interrogator time to process and transmit the data to an onboard DAC. This accounts for the delay between the packet and data. Five packets have been captured, and five packets have been decoded. The circled packets 1 through 3 are easily seen in the demodulated audio response.

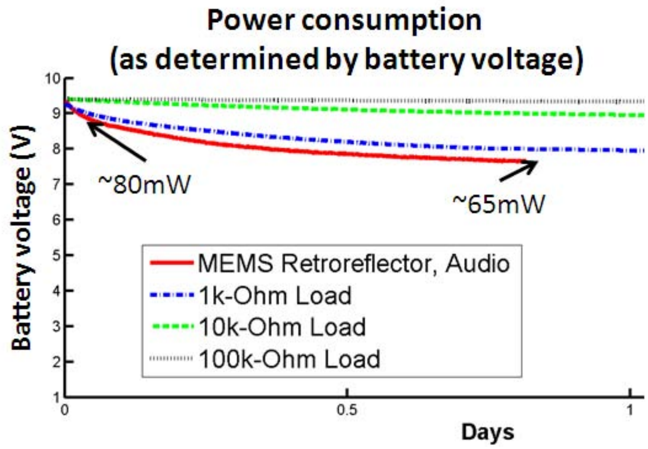

Figure 14: Load data for single Energizer brand 9 V batteries. The batteries were loaded with 1 kΩ, 10 kΩ, and 100 k***Ω*** resistors. The MEMS retroreflector is also shown over the same period while actively modulating Mary Ellen Carter by Stan Rogers.

5.2 Field Tests

Through collaboration with NovaSol Corporation in Honolulu, HI, the project team was able to evaluate the long-range performance of the MRR prototype using a state-of-the-art CW 1550nm laser interrogation system. The specifications of the NovaSol CI4 interrogator are summarized in the inset of Figure 15. Using this interrogator the MRR prototype was tested at 70m, 630m and 1.9km at the Bellows Marine Core Training Area (MCTAB) in Waimanalo, HI. The background image in Figure 15 illustrates the 1.9km communication link established between the MRR and the CI4 systems. The CI4 interrogator uses a fast steering mirror to remove tilt aberrations caused by atmospheric turbulence thereby improving the received signal power from the MRR. Analysis of the angle of arrival data from the fast steering mirror provides statistical information on the level of atmospheric turbulence. On the day the MRR system was evaluated, the C_n^2 turbulence coefficient was 3.3e-13 $m^{-2/3}$, with corresponding Fried parameter, r_0, equal to 0.7cm and scintillation index equal to 1.23.

A received data packet from the MRR to the NovaSol interrogator can be seen in Figure 16. For testing, the MRR was programmed to repeatedly transmit the 12-bit data pattern "111000010101." Here it can be seen that a 200kHz bit rate was successfully transmitted with a modulation contrast of approximately 12%. To improve the CI4's ability to detect the MRR data stream, the driver power supply was increased to 12V for these tests, providing an improved SNR ratio. With the 9V supply, the modulation contrast approaches the noise floor caused by atmospheric turbulence.

A summary of the test results at all tested distances can be seen in Table 1. The modulation contrast and received signal power reported correspond to driving the MRR with an external driver signal, which corresponded to a 150V peak-to-peak, 6kHz square wave. This was performed to evaluate the optical performance of the modulating retroreflector independent of the onboard low-power driver electronics. In their current configuration, the results suggest that the CI4 interrogator system should be able to establish a communication link with the MRR at a distance of up to 5km, while maintaining a received signal power approximately 15dBm above the minimum sensitivity of the InGaAs photodetector used to demodulate the signal.

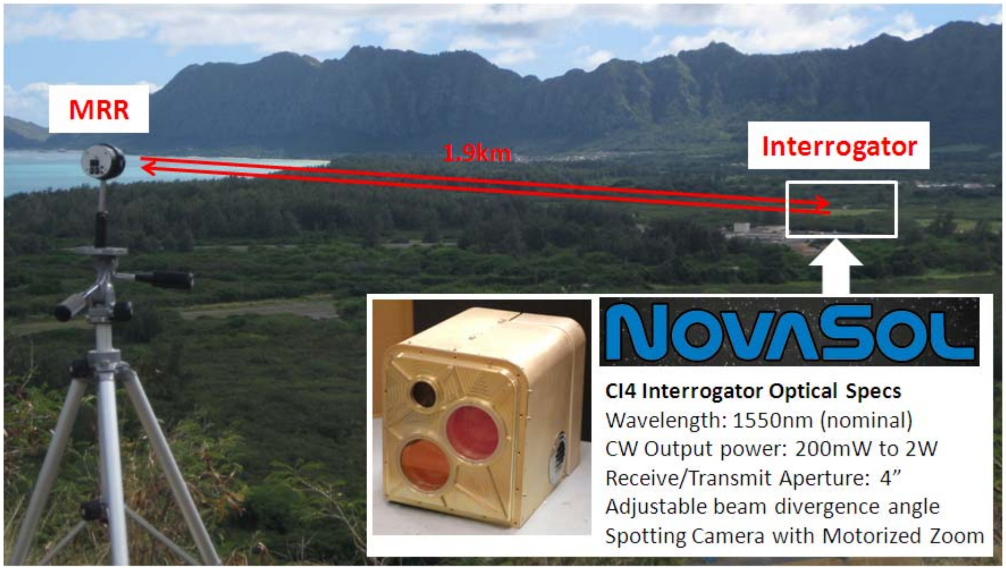

Figure 15: MRR field testing performed at Bellows Marine Core Training Area (MCTAB), Waimanalo, HI. The MRR prototype was tested at 70m, 630m and 1860m using new low-power resonant LC-boost electronics.

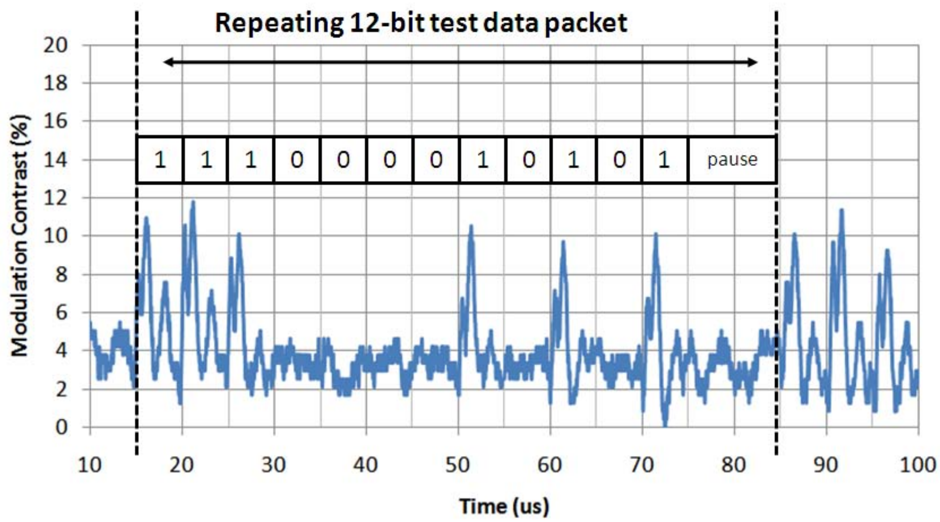

Figure 16: Received test data packet at 1.9km: 12V DC supply, 12% modulation contrast, 200kHz bit rate.

Table 1: Field test results summary. Results suggest NovaSol CI4 and MRR retroreflector are capable of establishing a communication link on the order of 5km.

Distance (m)	Beam Divergence (mrad)	Interrogator Transmit Power (dBm)	Interrogator Detected Power (dBm)	Normalized Power at 1.4mrad Divergence	Modulation Contrast: External Drive Voltage (150V, 6kHz square wave)
70	1.4	20	-17	-17	85%
630	1.4	20	-24	-24	80%
1860	0.8	27	-34	-46	70%
5000 (extrapolation)	*0.2*	*27*	*-45 (sensitivity limit = -60dBm)*	*NA*	*>60%*

6 CONCLUSION

In this STTR Phase II program the project teams successfully built on the Phase I work to design, develop and test a low-power, light-weight and low-cost modulating retroreflector (MRR) system, using a MEMS deformable mirror, for free-space covert optical communication and remote sensor interrogation. The central component of the prototype is a MEMS modulator mirror. The system, optimized for performance at 1550nm, and has a field of view of 60 degrees and uses "wake-up" circuitry to control a low-power shutter that remains closed between data transfer for covert operation. The system's compact driver electronics employs power scavenging and resonant properties for minimal power consumption and extended autonomous operational life. The MRR prototype system developed in this program was capable of providing 180kbps data rates using a single 9V battery for a 24-hour time period. A field test has demonstrated an optical communication links of up to 2km and shown the MRR node technology to be capable of much longer links limited only by the intensity of the interrogator beam. Alternatively, the range could be extended for a given interrogating source by increasing the aperture of the MRR system by increasing the size of the MEMS modulator and retro-reflector facets which can quite easily be scaled up to sizes of up to 5cm using the MEMS modulator fabrication technology.