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## MEMS MODULATED RETROREFLECTORS FOR SECURE OPTICAL COMMUNICATION

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#### ABSTRACT

A communication node enabled by a micromachined mirror is described, along with design, fabrication and evaluation approaches used. The micromirror is capable of switching in several microseconds between two states - one planar and reflective and one corrugated and diffractive. It is used as one facet in a corner-cube retroreflector that can communicate by returning a temporally modulated beam to an interrogating laser transceiver. Design of a very low-cost modulator device suitable for use as a communication node at ranges of several hundred meters is detailed. Fabrication approaches are developed for the micromirror to minimize the number of layers and process steps needed and to make use of scalable, high-volume thin film manufacturing techniques. Ultimately, a process comprised of three thin film depositions, two lithographic patterning steps, and one timed etch produces a robust and easily mass produced device. The devices that were tested featured up to 10:1 modulation of an incident beam and allow robust, secure optical switching through free space. The modulator was assembled with two orthogonal facets to comprise a retroreflector, and adequate orthogonality is demonstrated for communication over the intended range. Intrinsic stress behavior of tensile thin films are exploited to achieve nanometer scale flatness in the unactuated device, and a compact electronics driver is used to encode data and frequency modulate the active device. Electromechanical device behavior during electrostatic actuation is quantified. A functional prototype communication system using the modulated retroreflector and a telescope containing a 1.5µm wavelength laser and photodetector decoder is described, and secure communication is demonstrated over a free space path.

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#### INTRODUCTION

Retroreflectors have been used in optical sensing systems for some years, mostly as passive components that return incident laser pulses to the location of the pulsed laser source, allowing round trip time of flight detection and consequently precise distance measurement. Perhaps the most well known experimental use of passive corner-cube retroreflectors was for precise measurement of the earth-moon separation, using retroreflector arrays placed on the moon by Apollo 11 astronauts [1]. Active retroreflectors are a more recent invention, and are generally described as retroreflectors that can modulate the intensity of continuous wave or pulsed laser beams before returning them to the source. These so-called modulated retroreflectors (MRRs) offer an intriguing option for laser communication because they automatically return remote information (without beam steering) to an interrogating source location, and because the only power required at the remote MRR communicating node is that required to encode information (modulation) on the device: no laser source is needed at the MRR. The concept dates at least as far back as 1991, when it was first patented in an embodiment comprised of a retroreflector and a liquid crystal shutter [2]. Subsequently, researchers at the Naval Research Laboratory made considerable progress in developing MRRs using multiple quantum well (MQW) shutters [3-5]. These devices offer bandwidths of tens or hundreds of MHz, and can be quite compact. The MQW approach works only over a narrow range of interrogation laser frequencies, and is relatively expensive to manufacture. As a result, it is well suited to tasks such as ground-unmanned aerial vehicle communication or long-range point-to-point laser communication, but it is not suitable for dense mesh networks or low-cost remote-sensing applications.

A number of groups have developed very short range MRRs using microelectromechanical systems (MEMS) using both MEMS corner cubes [6-7] and microscale cat's eye retroreflectors [8-9]. These promise low cost, but offer a maximum range limited to several tens of meters.

The present work is intended to fill a gap in these approaches: MEMS-based MRRs suitable for low-cost, compact communication over hundreds of meters. A compact, low-power device has been developed to detect and modulate an incoming laser beam, and then return the modulated signal to the location of the sender. The MRR at the heart of this device consists of a MEMS based electromechanical modulator combined with a passive retroreflector: a hollow corner cube. The modulator serves as one (or more) of the three reflective surfaces on the retroreflector. The MEMS modulator has the characteristic that it can be made to act as a plane mirror, maximizing the amount of light that is retroreflected, or it can be made to act as a non-plane (corrugated) mirror, reducing the amount of light that is retroreflected. Operation of the device uses only microwatts to milliwatts of power depending on modulation frequency. The modulation frequency can range to at least a megahertz with conventionally processed MEMS fabrication tools and materials.

Data to be sent from the MRR could include voice communication, remotely sensed environmental information, or identification information. A key attribute of this system is that the transmission power and pointing control required for longdistance communication are delivered by the *interrogating* beam (through retroreflection). That is, the strength of the interrogating beam determines the strength of the returned beam. Furthermore, the noise-limitations for the system are constrained primarily by the quality of the receiver co-located with the sending beam. Almost no power is required at the retroreflecting modulator.

In this paper, a prototype laser communication system made with the MRR is introduced. In that prototype system, analog audio data from a microphone is frequency modulated and used to drive the MEMS optical modulator that is embedded in a wearable hollow retroreflector. The MRR unit is interrogated by a compact laser transceiver system that is comprised of a  $1.55\mu$ m wavelength, 10mW laser, a magnified optical visible channel and receiver, an avalanche photodiode detector, a frequency to voltage demodulator, and an amplifier and audio output signal. With this system, secure one-way audio communication over several hundred-meter range has been demonstrated.

#### SYSTEM COMPONENTS AND EVALUATION

The performance of modulating retroreflector sensor system can be characterized by its bandwidth, size, power consumption, cost, and range. A particular need exists for systems with bandwidth greater than 100khz, size less than 100cm<sup>3</sup>, cost less than \$100, and range up to 1km. Though MRRs have been the subject of study for more than thirty years, the devices that have been produced to date are often costly and have limited range. The work described in this paper

is motivated by the desire to demonstrate inexpensive MRRs with sufficient optical cross section to enable extended range communication with low power at the remote node.

The core concept is illustrated schematically in Figure 1.



Figure 1: Core concept: An electrically controlled MEMS mirror serving as one facet in a hollow corner cube retroreflector optically modulates an interrogating laser beam, returning encoded light to the source location, where it is decoded.

Our MRR MEMS device has the characteristic that it can be made to act as a normal plane mirror, or it can be deformed, using fast, low-power electrostatic actuation. The device maximizes returned light intensity when the MEMS mirror is planar, and minimizes it when the MEMS mirror is deformed. As a result, the intensity of the returned beam can be modulated by up to 90%.

To modulate the intensity of the interrogating laser beam, a reflective MEMS mirror was designed that is optically flat in its "off" state and optically scattering in its "on" state, thereby reflecting most of the incident beam energy out of the reflection path. The design architecture for the modulator, illustrated in Figure 2, uses electrostatic actuation to deform the reflective modulator mirror surface. The device is built upon an optically flat, electrically conductive silicon substrate that also functions as one electrode of a capacitor. The other electrode, deformed by electrostatic forces, is formed using a surface micromachining technique. A non-conductive silicon dioxide film is first deposited on the silicon substrate. This material functions as both the sacrificial layer that sets the gap between the electrode and the actuator membrane, and as the structural support for the mirror layer. A non-conductive, tensile silicon nitride film, with an additional reflective thin film of gold is deposited on top of the oxide. This nitride layer forms the flexible upper membrane of the electrostatic actuator. Its gold coated surface functions as the reflective mirror surface.

Electrostatic actuation is an effective way to deform thinfilm mirrors capable of achieving high angular deflection. Electrostatic actuators draw essentially zero current, consume almost no power, exhibit no hysteresis, and are relatively easy to fabricate in high-volume processes. Using commercial semiconductor batch processing techniques, per unit fabrication costs can yield devices at a few dollars each.



Figure 2: Top: Cross sectional illustration of MEMS modulator. In its "off" state, the mirror surface is flat. In its "on" state the mirror surface becomes corrugated with peak to valley surface height measuring about 350nm. Bottom: interferometric microscope 3-D image (with exaggerated vertical axis) showing a section of the modulator in the on state.

The modulators were tested by analyzing their surface with an interferometric surface-mapping microscope and by modulating them while illuminating with a HeNe laser and recording far-field zero-order intensity fluctuations using a fast photodetector. When unenergized, the modulators exhibited good optical surface quality, with deviation from flatness of about 8nm-rms measured over a 1mm square area using an interferometric surface-mapping microscope.



Figure 3: Top left: Photo of modulator chip. Top right: Interferometric surface map of actuated modulator. Bottom: Cross sectional profile of modulator surface with 75V actuation applied. The measurement shows modulator actuator deflection of over 350nm.

Far field optical modulation was measured as a function of applied modulator voltage at low frequency, by recording the

peak change in photodetector voltage in the far field for a detector located at the zero order reflection spot of an incident HeNe laser. The deflection and modulation data are plotted as a function of applied modulator peak voltage in Figure 4.

The fabricated modulator devices were capable of operation at frequencies of up to 1MHz, and exhibited a slight resonance at about 550kHz, as shown in Figure 5.

The devices were integrated into hollow corner cube retroreflectors by aligning the modulator chip and two solid, gold coated silicon chips in mutually orthogonal orientations. When properly aligned, the devices were cemented into place and mounted in a cylindrical housing, and then inserted into a wearable MRR unit with microphone audio input, as depicted in Figure 6.

The transceiver for the system was retrofitted from a magnified monocular device. A block diagram of the functional elements of the transceiver is illustrated in Figure 7.

High-fidelity audio communication using this novel MRR link was demonstrated over a 200m link with the prototype wearable MRR (Figure 8), and tests evaluating maximum range, power consumption, signal to noise ratio, and system performance are currently underway.



Figure 4: Modulator quasi-static performance data: measured peak deflection and peak intensity of the zeroorder deflection as a function of peak applied modulator voltage. Inset picture at left shows the far field diffraction pattern with 70V applied, and a superimposed circle corresponding approximately to the photodetector's measurement pupil. Inset picture at right shows an interferometric surface measurement of the modulator with 70V applied.



Figure 5: Modulator dynamic performance data: measured peak zero-order signal intensity as a function of peak applied modulator voltage, for 45V (lower curve) and 65V (upper curve) modulator voltage. Modulator response exhibits slight resonance at ~600kHz drive frequency.

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Figure 6: MRR (Right), protective housing and drive electronics (Left) and wearable unit (Top). The unit measures about 100mm x 75mm x 50mm.



Figure 7: Block diagram of the transceiver. A 10mW infrared laser interrogates the remote MRR, Returning (modulated) light is received by a 60mm aperture, and is detected by a fast photodiode. The resulting electronic signal is demodulated and amplified, allowing the receiver to hear audio from the remote node. A beam splitter allows direct imaging of the MRR to establish line-of-sight communication. No pointing is required at the modulator node, which has an angle of view of about 60°.



Figure 8: Photographs of wearable MRR unit (Top) and transceiver (Bottom)

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