MEMS Optical Modulator Technology Overview

The BMC MEMS Optical Modulator, shown in Figure 1, was designed for use in free space optical communication systems. The modulator is a reflective diffraction grating with controllable groove depth. It is capable of continuous far field intensity variation of a reflected laser beam by switching between an unpowered flat mirror-state to a powered diffractive state. The device design is based on BMC's heritage deformable mirror technology that uses hysteresis-free electrostatic actuation to periodically deform a continuous mirror face sheet. The diffraction efficiency of the specularly reflected beam is a function of the modulator groove depth, which is controlled through electrostatic actuation of the mirror surface. Laser intensity modulation has been demonstrated to be better than 90% contrast at wavelengths from 633nm to 1550nm. Using gold or aluminum reflective coatings, the diffractive nature of the device offers a broadband solution to several laser amplitude modulation applications.

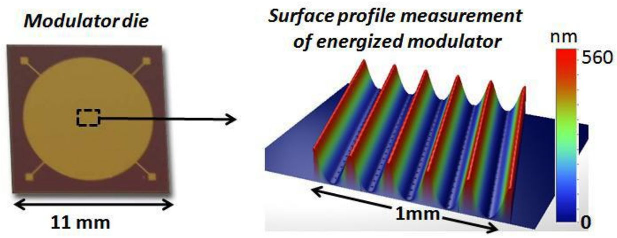

Figure 1. BMC MEMS Optical Modulator die (left) and surface Profile measurement of energized sub region (right).

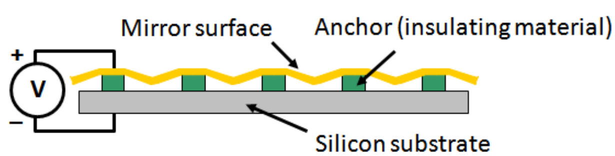

Figure 2. Cross section of electrostatically actuated MEMS Optical Modulator.

The modulator is fabricated on an optically-flat, electrically-conductive silicon substrate that functions as one electrode of an array of elongated electrostatic actuators, as illustrated in Figure 2. The mirror surface acts as the other electrode, which is fabricated using MEMS surface micromachining and consists of a thin, gold- or aluminum-coated silicon nitride layer. The modulator mirror surface is suspended and electrically isolated from the substrate by an array of silicon oxide anchor supports. With the application of a voltage (V) between the modulator reflective surface and the device substrate, the mirror actuators experience deflection corrugating the mirror surface. The device micro fabrication process has the sole purpose of producing optical modulators in a cost effective manner using commercial semiconductor batch processing techniques. Each fabrication step is based on the standard semiconductor fabrication process, providing high volume production capability. The grating profile of the deflected modulator is similar to that of a symmetric scribed or ruled grating. Our manufacturing processes are capable of producing a maximum modulator groove depth (or stroke) on the order of 1 µm and a minimum pitch on the order of 50 µm. A trade-off exists between achievable modulation contrast and dynamic response in the design of the modulator electrostatic actuator. A reduction in actuator pitch (span) increases the actuator stiffness and resonance frequency which improves switching speed but may reduce the maximum achievable laser modulation contrast for a given wavelength due to limitations on the maximum drive voltage. **Modulators spanning a substantial portion of the design space have been demonstrated and device performance can be customized to user specifications.**

Unpowered Surface Figure

The typical surface figure of an unpowered MEMS Optical Modulator is shown in Figure 4. As previously discussed, the device is manufactured using surface micromachining processes on a polished silicon wafer, which produces a high-quality mirror surface with local roughness of less than 2nm RMS. Each actuator row has a series of micron-sized holes in the mirror facesheet, required for device fabrication process, which yields a typical fill factor greater than 99.8%. Due to the nature of surface-micromachining, some periodic features remain on the mirror pattern, as well as etch access holes used for the MEMS release process. The resulting surface flatness of the modulator active aperture can be better than 20nm RMS. At a 1550nm wavelength, the overall reflective losses due to diffraction caused by these periodicities and fill factor are less than 4% of the incident beam power.

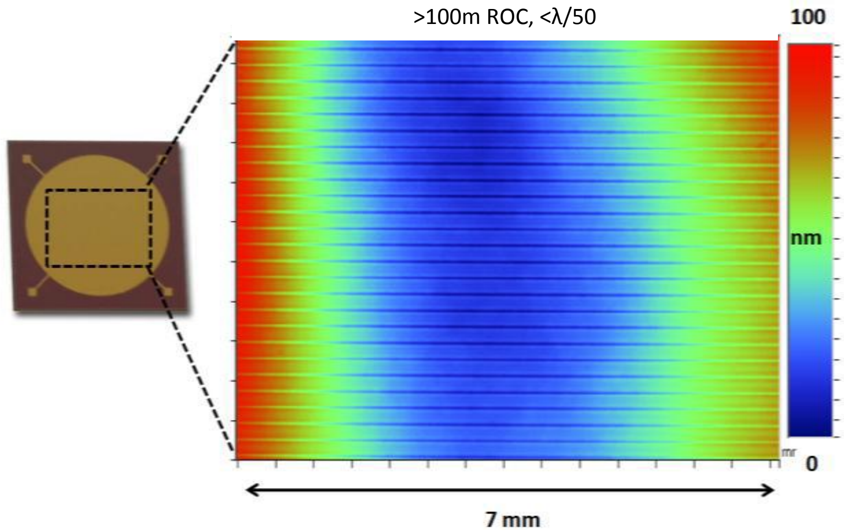

Figure 4. *Typical MEMS Optical Modulator surface figure.*

Optical and Electro-Mechanical Performance

The optical and electromechanical performance of a typical 200 µm pitch modulator with 185 µm span actuators can be seen in Figure 5. 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. As shown, a sample modulator is capable of achieving slightly greater than 98% modulation contrast with 630nm illumination at 0 degree AOI at an applied voltage of approximately 140V. At higher angles of incidence, the modulator actuators needs to deflect further to achieve the same modulation contrast. Therefore, as AOI is increased, the modulation contrast curve in Figure 5 shifts to the right (see dotted line). If modulator actuator pitch (or span) are reduced, the deflection and modulation contrast curve in Figure 5 shifts to the right with higher required voltages for given deflections.

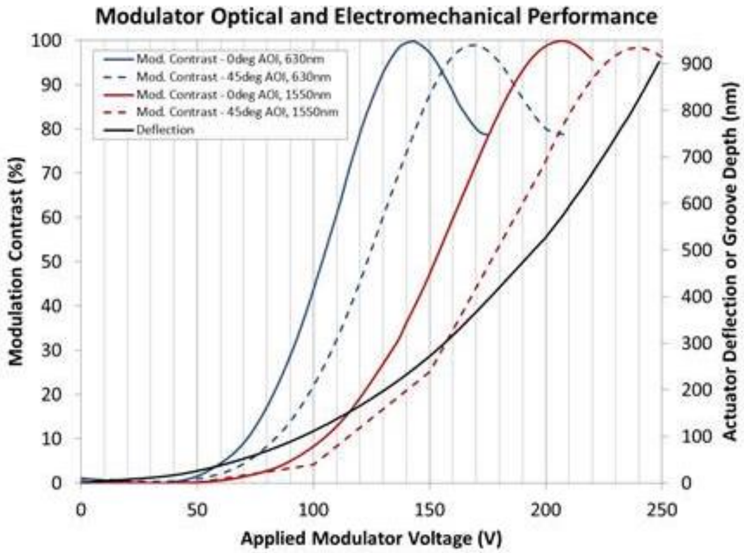

Figure 5. *Actuator deflection and modulation contrast behavior for a typical 200 µm pitch modulator with a 185 µm span (not all devices are capable of the above performance).*

The dynamic step-response performance of the modulator described above at atmospheric pressure can be seen in Figure 6. In this modulation contrast measurement, the device exhibits an over damped response with a faster settling time when transitioning from "on" to "off" states. When energizing, the modulator achieves 50% contrast in about 7 µs and 98% contrast in about 40 µs. This is largely due to an air dampening phenomenon known as squeeze film damping. As discussed above, increasing actuator stiffness can also be used to reduce settling time. Actuator spans on the order of 100 µm have demonstrated full contrast settling times of better than 7 µs at atmospheric pressure.

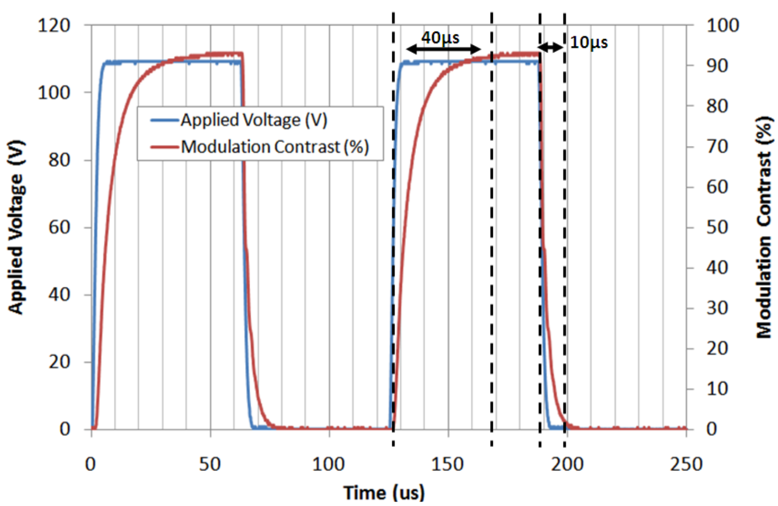

Figure 6. *Dynamic response of a 185 µm span modulator to a 0 to 110V, 8kHz square wave, as seen by the photo detector measuring the 0th order diffraction signal.*

With the development of new packaging solutions and drive electronics, the device could also be operated in a partial vacuum environment and theoretically controlled at frequencies greater than 1MHz.

Laboratory Optical Modulator System

BMC currently offers the Optical Modulator for laboratory use in a compact, easy-to-integrate package. The Laboratory Optical Modulator is mounted on a PCB and secured in a standard 1" optical lens tube. The modulator is electrically connected to the PCB and wired to a standard female BNC connection located at the rear of the housing. In the standard housing the user has up to a ±20° field of view. Input signal can be provided by an amplified signal.
The Optical Modulator is the enabling component in the Reflective Optical Chopper. This device couples a high-speed precision amplified TTL signal with the Optical Modulator to provide the user with a complete laboratory system. This system can be used as a stand-alone device for high-speed optical chopping and, in tandem with a user-supplied TTL signal, a custom duty-cycle optical modulator.

Figure 7. *Picture of the Laboratory Optical Modulator component*

When mounted as one facet of a hollow corner cube retroreflector, the BMC MEMS Optical Modulator is capable of passively returning light from an interrogating laser source while simultaneously modulating its intensity for asymmetric communication; such a system is known as a modulating retroreflector and it is illustrated in Figure 8.

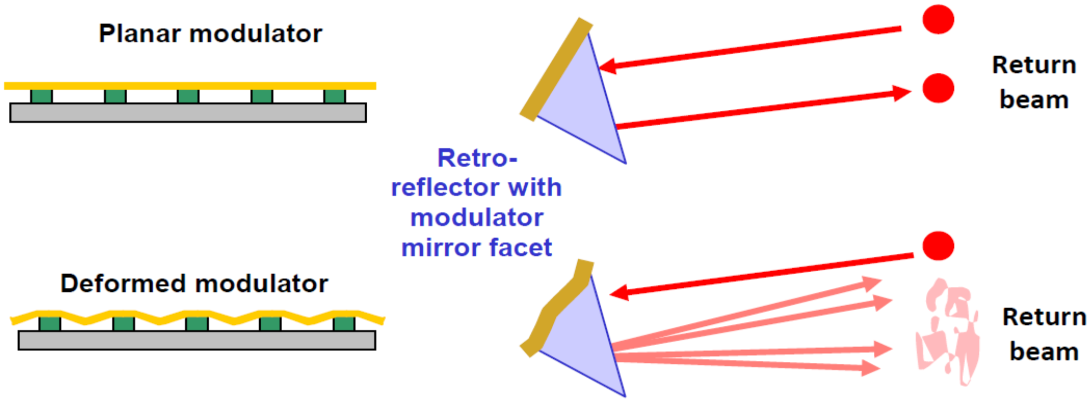

Figure 8. *Operation of MEMS modulator and hollow corner cube retroreflector.*

The MRR optics consist of 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 gold-coated silicon die measuring 11mm on a side. The third mirror facet is the BMC MEMS Optical Modulator, which has similar dimensions and a gold-coated active aperture that measure 9mm in diameter. The three die are aligned and bonded using a proprietary process to produce the retroreflector (Figure 9), which has parallelism better than 30 arc seconds. The assembly is located on the axis of the cylindrical MRR housing behind a protective window.

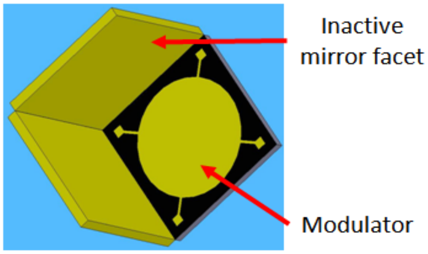

Figure 9. *Illustration of hollow corner cube retroreflector using the BMC MEMS modulator.*

Figure 10. *Picture of Laboratory MRR component*

Laboratory MRR System

BMC currently offers the MRR for laboratory use in a compact, easy-to-integrate package. The Laboratory MRR is secured in a standard 1" optical lens tube. The modulator is wired to a standard female BNC connection located at the rear of the housing. In the standard housing the user has a ±20° field of view. Input signal can be provided by an amplified signal or the Reflective Optical Chopper driver.

Application Note

Custom MRR System

As part of a 2008 Army contract, BMC, in collaboration with researchers at Boston University, developed the prototype mobile modulating retroreflector (MRR) system shown in Figure 11. The Mobile MRR system is capable of providing continuous asymmetric free space optical communication at 180kHz over a 24 hour period using a single 9V battery supply.

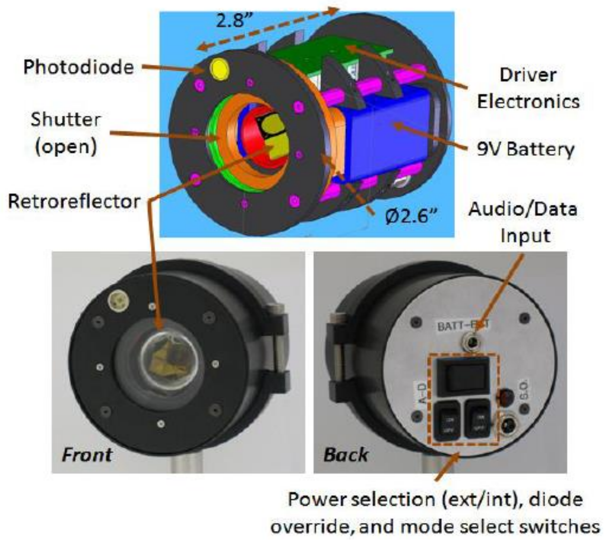

Figure 11. *Fully assembled and functional Mobile MRR prototype.*

The assembly is located on the axis of the cylindrical Mobile 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 Mobile MRR housing does not obstruct the incident or reflected interrogator beam, provided that the system field of view (FOV) is limited only by the hollow corner cube geometry, which is approximately 60° (full-width-half-max) as seen in Figure 12.

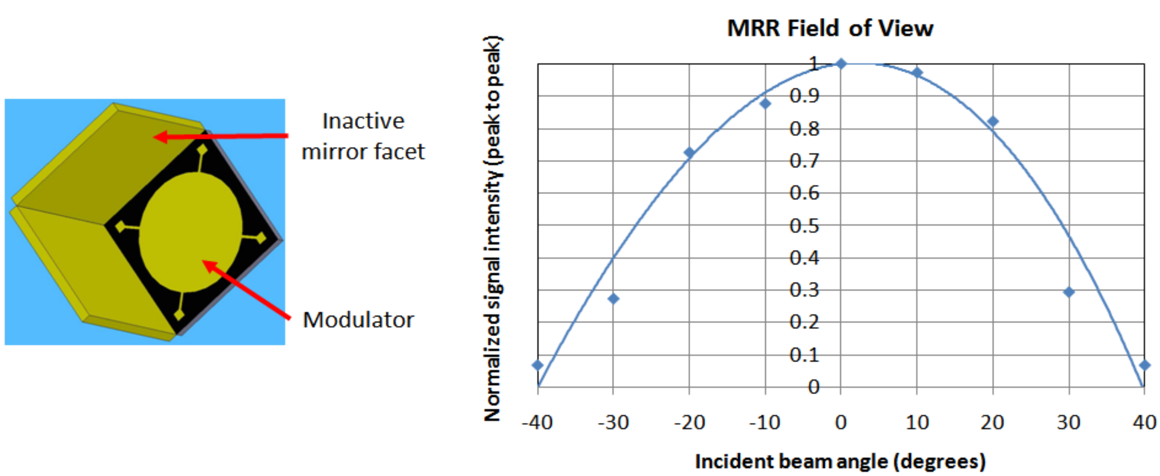

Figure 12. *Illustration of hollow corner cube retroreflector using the BMC MEMS modulator (left). Measured Mobile MRR field of view (right).*

A primary component of the Mobile MRR system is a compact, low-power, high-voltage driver design used to control the modulator using a single 9V battery. 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 180kHz. This inductor-capacitor (LC) boost circuit is also capable of recycling power, providing continuous operation lifetimes exceeding 24 hours and intermittent interrogation lifetimes on the order of 6 months.

Figure 13 contains data for the drain response of a 9V Energizer battery 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. Total power consumption for the system during these tests remained below 100mW. The full MRR system was field tested using a 1550nm CW laser interrogation source developed by Nova Sol Inc., shown in Figure 14. While a 2km link was established, extrapolation of test results suggests the interrogator and Mobile MRR are capable of extending their range to approximately 5km.

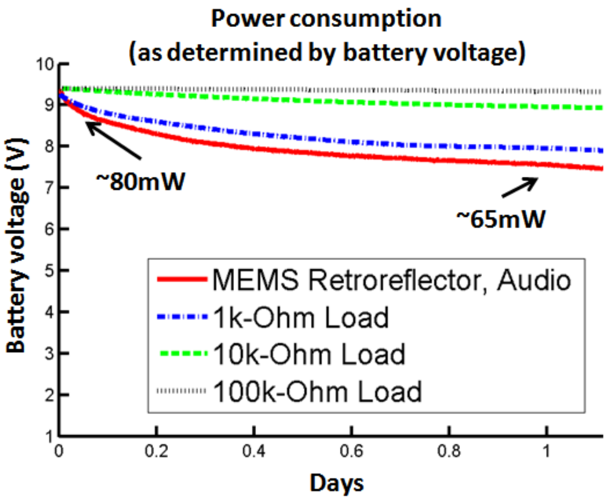

Figure 13. *Mobile MRR power consumption, as evaluated by battery voltage testing.*

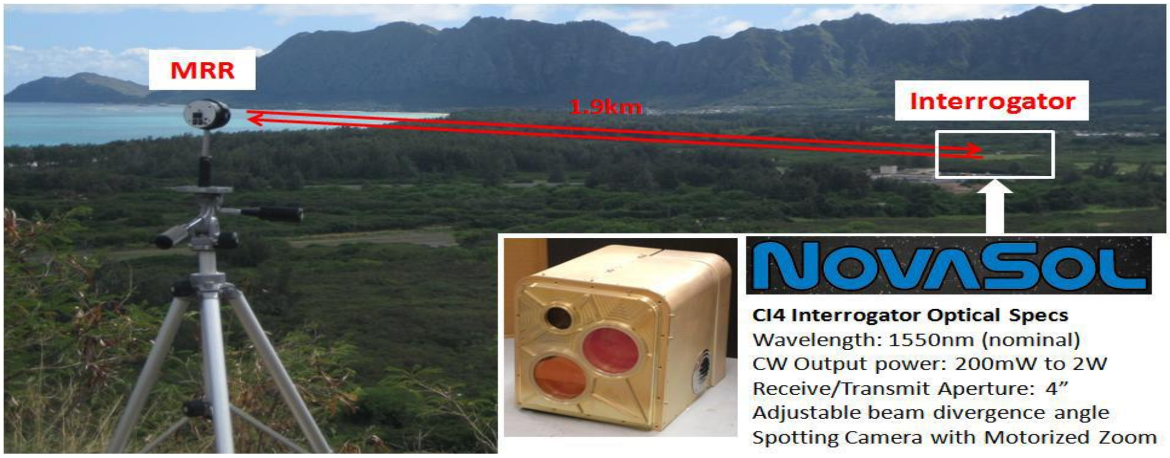

Figure 14. *Illustration of hollow corner cube retroreflector using the BMC MEMS modulator (left). Measured retroreflector field of view (right).*

The BMC Mobile MRR system has four inherently advantageous characteristics over other remote free-space lasercom technology:

- **Pointing and tracking subsystems are not required.** Since the retro-reflector automatically returns the beam to its source, the system does not require pointing and tracking subsystems to establish a link between its nodes.
- **High signal power density and increased signal security.** The MRR directs the return signal along a narrow pathway, rather than over a wide angle, thus improving signal power density and also reducing the probability of third party signal interception.
- **Low power consumption.** The Mobile MRR operates as a "passive source" that does not emit its own radiated power. This feature greatly enhances battery life at the remote node, which could be a soldier, a passive sensor or a surveillance location. This strength of the return beam is directly proportional to the strength of the interrogating beam. It is also proportional to the 4th power of the retroreflector aperture diameter, which can be eaily scaled in the MEMS manufacturing process. The only battery power supplied at the remote node is that required for sensor operation, data production and electrostatic modulation.

- **Multiple application mamagement capabilities.** The reflectance spectrum of the MRR is broad, allowing the possibility to manage multiple systems operating at different wavelengths. For example, the MRR can modulate an illumination beam sent from a Mid-IR (850nm) laser and return it at a slow blink rate to a pair of night vision goggles for friendly identification, while intermittently modulating a 1550nm laser bean with encoded data, such as location and user identification. Competing systems are limited by narrow bandwidth and do not provide this ability.

For additional information on device performance and availability please contact:

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