MEMS-based interferometric modulator for display applications

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ABSTRACT

Microelectromechanical Systems or Structures (MEMS) incorporate a set of attributes which make them uniquely suited for an expanding array of applications. The field of displays is one that has been a particular beneficiary of this class of devices. At least one display product has been introduced, and there are numerous products on the verge of being introduced or which are under development. Many segments of displays are experiencing rapid growth. Reflective displays in particular are growing in importance due to their inherent low-power consumption and ambient light performance. Unfortunately, the technical challenges for all these segments are such that traditional solutions, primarily LCD based, are limited in their ultimate performance. These are challenges for which MEMS are well suited, and there are several efforts underway to exploit this fact. One such effort, which is based on a device known as an Interferometric Modulator (IMod), is described here. A brief review of MEMS based display concepts is also included.

Keywords: MEMS, thin film optics, flat panel display

1. INTRODUCTION

With the advent of the laptop computer, computer based presentations, and more recently the Internet, the need for high information content displays in a portable format has been on the increase. Displays originated in the form of the Cathode Ray Tube or CRT but the development of the Active Matrix Liquid Crystal Display (AMLCD), which is the predominant technology for Flat Panel Displays, has had a major impact on this area. CRTs no longer dominate the field and are being rapidly overtaken, in terms of quantities manufactured. In addition, recent years have seen an explosion in the number and variety of portable display oriented electronic products beyond the realm of the laptop computer. These include cellular phones, pagers, portable digital assistants, electronic books, desktop projectors, and head mounted displays. Early versions of these products required only minimal display performance in terms of resolution and gray scale. Increasingly, however, they are required to portray higher resolution (>VGA) graphical information and color. With connectivity to networks (i.e. cellular, Internet) forcing higher bandwidth onto these products, the demands for display performance will only increase.

The reflective display is just one display type which is receiving a great deal of attention in recent years. Reflective displays are distinguished because of the fact that they utilize ambient light as their light source. AMLCDs, the basis for most laptop displays, are emissive displays in that they utilize a LCD array to modulate light generated by a backlight that is incorporated into the display system. Their emissive cousins, Field Emitter Displays (FEDs) differ in that the pixel elements themselves produce the light. In either case, at least two penalties are paid. In the first, energy is required to generate the light, which is one of the significant components in reduced battery life in portable products. The second is the fact that the ambient lighting environment, for example bright sunlight, can impose significant restrictions on perceived brightness and contrast.

No such limitations exist for reflective displays, which operate in a way in which humans are much more accustomed. That is to say that the human visual system was evolved to perceive things using reflected light. Examples of successful reflective static displays abound and include books, magazines, and works of art. Active displays, which are reflective have the potential to be readable in virtually all ambient lighting conditions while consuming minimal, and in some cases, no power. However LCDs, which provide the basis for all reflective displays currently in use, realize only a fraction of the potential of the reflective approach. This is primarily due to the fact that as much as 50% of the light or more is lost due to the need to use polarizers, in some LCD variants, as well as color filters and other loss mechanisms. A great deal of effort is being made to increase the performance of LCD based solutions, but it would seem that only incremental progress can be made given the fundamental restraints of the underlying modulation mechanism.

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2. MEMS DISPLAYS

In general, MEMS have a set of attributes which make them suitable for modulation elements in all kinds of displays. These can be summarized in the following:

High Speed – Depending on the geometry and dimensions of the structure, actuation times can be as short as tens of nanoseconds.

Digital drive – Most structures operate in a discrete or non-analog fashion. This simplifies the nature of the electronics used to drive them.

Low power – Because of the capacitive nature of MEMS that utilize electrostatic actuation, power consumption can be exceptionally low.

Wide temperature range – Conventional MEMS devices are fabricated from combinations of oxides, nitrides, polysilicon, or metals. These materials are very robust from a temperature, shock and UV exposure standpoint.

Hysteresis – Electromechanical memory is an inherent characteristic of many MEM structures and can be exploited for display purposes.

High reliability – Products and devices have already been demonstrated to have lifetimes on the order of 15-20 years or more.

A number of avenues for applying MEMS to displays, are currently being explored and are at varying levels of maturity. Each approach has its own merits and limitations, however all benefit from the preceding list to some extent. MEM modulators which are being developed or have been considered for use in displays can be categorized by the modulation mechanism which includes; reflective, diffractive, light valves, and those based on total internal reflectance. A brief survey of current efforts and their application is included in the following.

2.1 Reflective MEM Modulators

The Digital Micromirror Device (DMD) from Texas Instruments represents the most mature of the MEM modulators and is currently available as the core of a projection system display[1]. DMDs can be described as arrays of micromachined tiltable mirrors which have been fabricated, using surface micromachining techniques, on an active CMOS substrate. The mirrors are fabricated in the form of aluminum alloy pedestals which are supported from the surface of the substrate via a torsion hinge. The substrate, which resembles a SRAM, is used to provide control signals to electrodes which actuate the pedestal and cause it to tilt backwards and forwards within 20 degrees of travel. When positioned at the focal plane of an appropriately designed optical system, the DMD can produce high-resolution imagery for display on a large viewing screen. The optical system is designed such that light is either directed towards the projection screen or into a “light dump”. Color is provided either through the incorporation of a synchronized color filter wheel in the light path, or through the use of three DMDs, each responsible for a particular Red, Blue, or Green color channel. The DMD is relatively fast with switching times on the order of 10 μs and pixel sizes of on the order of 16 μm X 16 μm. While the DMD relies on reflection as the modulation mechanism, it is limited to display systems that use a fixed viewing angle. Thus it is not well suited for applications which require directly viewed large area displays which can be seen from arbitrary angles.

Reflective MEM modulators also occur in the form of single or dual mirror scanning assemblies instead of arrays. The underlying principle being to generate a raster scanned image by the proper synchronization of mirrors for horizontal and vertical scanning. Researchers from Berkeley[2], and the MicroOptical Corporation have been engaged in development efforts to pursue this approach. The Berkeley device utilizes polysilicon mirrors which are rotated during fabrication into a position which is roughly perpendicular to the substrate, along with supporting microfabricated optics. Once in position, the mirrors may be rapidly oscillated by virtue of electrostatic comb drives to which they are attached. The scanner from the MicroOptical Corporation utilizes mirrors that are mechanically coupled and driven using both electrostatic and magnetic actuation schemes. These displays are suitable for projection or virtual imaging systems where an optical system may be readily incorporated.

2.2 Diffractive MEM Modulators

There are at least two efforts underway to exploit the properties of modulators that rely on diffractive effects. One effort, undertaken by Silicon Light Machines, relies on a device known as the Grating Light Valve or GLV[3]. The GLV comprises an array of narrow self-supporting silicon nitride ribbons that are coated with a reflective aluminum film. The beams are suspended above the substrate by a distance of ¼ the wavelength of light of interest, and are configured so that alternate ribbons can be actuated downward by the application of voltage. The spacing between adjacent ribbons is such that in the undriven state a single device, comprising say five ribbons, behaves like a mirror. Application of a voltage changes the behavior of the array to that of a diffraction grating. The GLV is exceptionally fast, exhibiting actuation times of 20 ns. In addition, the device has inherent color due to the diffraction effect. Proper design of the optical system in conjunction with careful control over the period of each grating pixel, allows for the generation of a full color display. The same effect however, also limits the application of the GLV to fixed viewing angle applications like the DMD. Another grating based modulator, which has been developed at Case Western Reserve University, is known as the Micromotor Grating Optical Switch[4]. In this device, a diffraction grating is fabricated on the surface of a polysilicon micromotor which allows the grating to be rotated with respect to an incoming light beam. Choice of materials and the grating period allows the device to act in either transmission or reflective modes. While seemingly not appropriate for display applications, the device is under consideration for roles as fiber and free-space switches as well as beam steering and scanning.

2.3 MEMS Based Light Valves

Light valves utilizing MEMS generally are devices that can selectively obstruct incident light. One rather unique device developed at MIT Lincoln Labs is described as a Microshutter[5]. Fabricated rather simply, the microshutter comprises an array of opaque flexible membranes fabricated from materials that result in an anisotropic stress gradient. Figure 1 shows a SEM of the structure. The substrate, which is transparent, is coated with a layer of ITO so that a voltage may be applied between it and the membrane. Only one end of the membrane is attached, so that when the membrane is freed during manufacture, the inherent stress gradient causes it to coil up very tightly thus no longer obscuring the area it once covered. Application of a voltage causes the membrane to flatten again until the voltage is removed, thus providing the modulation effect. These devices have switching times on the order of 40 μs and also have inherent electromechanical hysteresis. This approach would appear to be suited for both fixed viewing angle applications as well as direct view reflective displays. Researchers at Centre Suisse d'Electronique et de Microtechnique have worked on two other similar approaches. The first relies on polysilicon paddle fabricated such that by application of a drive voltage it may be actuated horizontally into a position which obstructs a hole through which light would normally propagate[6]. Alternatively, a large area array of switchable flaps has also been considered for display applications[7].

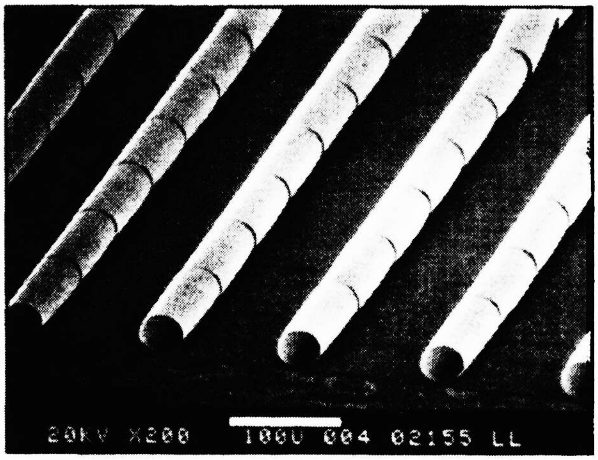

Fig. 1 A SEM showing the structure of the Microshutter light valve from MIT Lincoln Labs. Anisotropic stress gradients in the structural material cause the membranes to curl up in the undriven state. They flatten when a voltage is applied.

2.4 MEMS Based Total Internal Reflection (TIR) Modulators

TIR is another approach that has benefited from the capabilities of MEMS, and at least two similar devices have been explored. One, another entry from Lincoln Labs, comprises an array of deformable membranes which have been fabricated on a transparent substrate. The membranes, which are fabricated using a transparent material such as silicon nitride, are positioned so as to reside over regions of the substrate which have been patterned to form a protrusion. The area of the membrane which coincides with this protrusion, is roughened during the manufacturing process. Light coupled into the edges of the substrate at a suitable angle is normally trapped via the phenomena of total internal reflection. By applying a voltage between the conducting substrate and the membrane, the resulting contact causes the light to be coupled out of the substrate and scattered in a direction perpendicular to the plane. This is not unlike a device that resulted from a collaboration between the University of Michigan and Xeotron Corp.[8] Referred to as a Waveguide Panel Display, it differs only in that a blazed mirror structure is used to more efficiently couple the light out of the substrate. Both of these approaches can be considered emissive display candidates and would appear suitable for application to large and small area display formats.

2.5 MEMS Based Modulators Using Interference

The phenomena of interference is another effect which has been leveraged by MEMS as a method for modulating light. A number of micromachined structures have been developed though primarily for purposes other than display applications. Among the first researchers to use micromachined modulators that exploit interference was a collaboration between Sony and Delft University of Technology[9]. This device, a tunable interferometer array, was developed as a way of facilitating inter-chip optical communications. Comprising arrays of polysilicon/silicon nitride membranes fabricated using surface mircomachining techniques, they resemble Fabry-Perot interferometers in their structure and optical performance. Individual devices are on the order of 40 μm in length and width and actuation times are submicrosecond. More recently, two devices have emerged which are electrostatically tunable Bragg mirrors fabricated using similar techniques[10,11]. These filters are geared towards the telecommunications market and offer much higher finesse than that which can be achieved with single mirror structures. Both require drive voltages ranging from 15V to 50V and are tunable over the range of 100nm or more. The use of multilayer dielectric mirrors or dielectric/air mirrors begins to suggest the performance diversity that is possible using interference. Researchers at Lucent Labs have produce yet another interference based modulator known as the Membrane Anti-Reflection Switch or MARS[12]. This novel device utilizes an actuatable membrane can be configured to act as an anti-reflection coating when it comes into contact with the substrate. With actuation speeds of less than 1 μs, the MARS is positioned for a variety of telecom applications including variable attenuators and passive fiber modulators.

3. INTERFEROMETRIC MODULATORS (IMods)

From the approaches described above, interference is particularly intriguing as a modulation mechanism when coupled with MEMS for several reasons. First, the dimensions of thin film optics are similar to those of MEM devices in that they are generally planar structures and thus afford good control over the important parameter of film thickness. Second, the actuation of MEM devices is most easily achieved in a direction which is perpendicular to the substrate and therefore also in line with the critical dimensions of an interferometric structure. Finally, the ability to produce a many different film combinations and dimensions makes it possible to craft modulators with well defined spectral reflectance or transmission functions of an almost arbitrary nature. This is especially advantageous in color displays for it allows for a great degree of control over the color gamut of the overall display. Overall, the relatively low losses that can be obtained in devices utilizing thin film optics is quite appealing from a display perspective. The term Interferometric Modulator or IMod has been coined to describe this class of optical modulators which are enabled by leveraging the intersection of thin film optics and MEMS.

3.1 IMod Theory of Operation

Etalon, Inc. is engaged in the development of IMod designs that are optimized for reflective display applications. Figure 2 illustrates the operation of one design, and figure 3 shows an actual IMod structure. The composition of the structure is relatively simple. A self-supporting metallic membrane, such as aluminum, is fabricated on the surface of a transparent substrate, nominally. Residing beneath the membrane, and separated by an insulating layer and air gap, is a conducting metal/metallic oxide stack. The viewer's perspective is through the substrate. When undriven, the IMod performs as an optically resonant cavity reminiscent of a Fabry-Perot. Consequently a reflective peak is produced in this state, the color and characteristics of which are determined by the value of the air gap. Representative peaks are show in figure 4. Application of sufficient voltage between the membrane and the stack causes the membrane to actuate and deflect into full contact with the stack. When this occurs, the IMod behaves in a fundamentally different mode. The stack acts to optically match the admittance of the membrane and the glass substrate. The result is the device becomes highly absorbing and appears black to the viewer. Figure 4 shows a theoretical spectral reflectance function for the device in the driven state. With substrate front surface reflections taken into account (approximately 4%), this should allow for a theoretical contrast ratio of 20:1, a figure which can be increased with the use of antireflection coatings.

The IMod is designed to function as a binary modulator, though limited analog operation is possible. Binary operation is preferred for two reasons. First the required drive electronics are simplified thus reducing cost and complexity of addressing systems. Second, binary operation allows for the exploitation of the electromechanical hysteresis that is associated with these kinds of MEM devices. This derives from the relative effect of the two forces that act on the IMod during operation, that of electrostatic attraction, and the mechanical restorative force of the membrane. The former grows in an exponential fashion as the membrane approaches the substrate, and the latter is linear. The result is that when the applied voltage is gradually increased, the membrane experiences increasing deflection until a point of instability, the collapse threshold, is reached and it suddenly actuates fully. The close proximity of the membrane to the stack now greatly reduces the amount of voltage required keep the membrane deflected. This creates a hysteresis loop which provides a memory effect which is very useful in creating display arrays. The characteristics of this loop are determined by the overall dimensions of the structure, as well as the thickness of the insulating layer. From a response time perspective, actuation times of less than 1 μs should be obtainable.

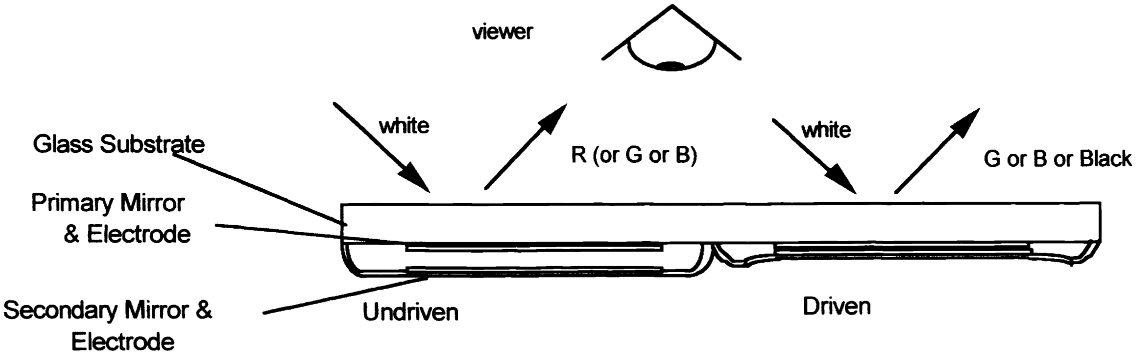

Fig. 2 Diagram of the operation of one IMod design. This design is optimized for use in a reflective display and is capable of full color operation.

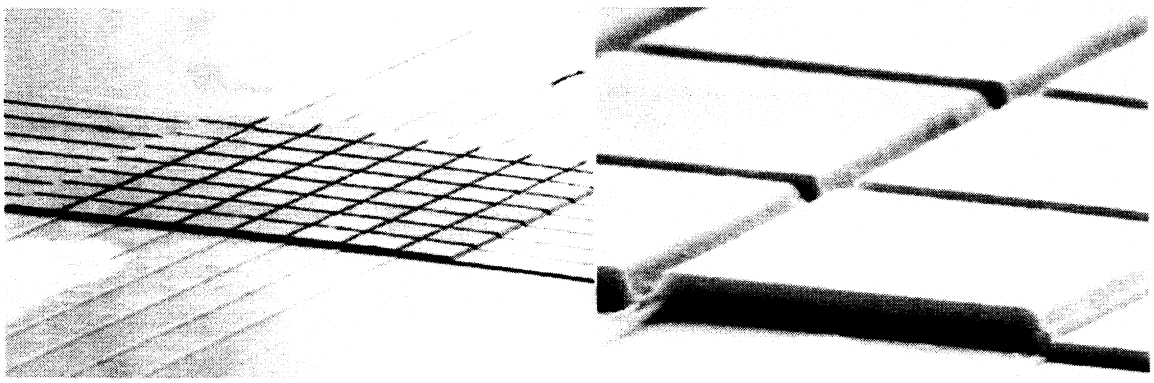

Fig. 3 Shows a SEM of a small 8X8 IMod array illustrating the basic structure of the device.

IMods are fabricated using a process known as surface micromachining, a method which is well known and provides a great deal of flexibility in materials and substrates. Fundamentally, the fabrication sequence is quite simple. The initial thin film stack is deposited and patterned using conventional deposition and photolithographic techniques. This stack can comprise a number of different combinations of oxides and refractory metals. The stack, which now serves as the primary electrode, is coated with an insulating film, and a subsequent sacrificial material. Deposited silicon is one candidate for it can be removed using a selective gas phase etch, though others are also possible. The sacrificial material is subsequently patterned and etched to form a "mold" over which the structural metal is deposited. A number of metals are also possible for this role, though the selection is somewhat limited by the need to maintain high reflectivity. Aluminum or aluminum alloys are generally employed during this step. This material is then patterned to form the IMod membranes, which also act as the secondary electrode. The sacrificial material is subsequently removed using a gas phase etch such as XeF_2, and the devices are ready for operation.

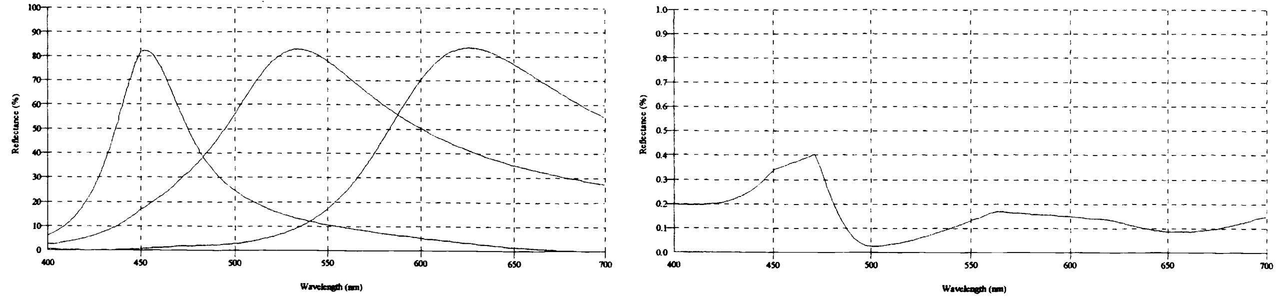

Fig. 4 Spectral reflectance function for the IMod. The plot on the left shows the response for several different color/(air gap dimensions): blue (350nm), green (130nm) and red (220nm). The plot on the right shows the response when the IMod is in the driven state. Note the expanded scale of this plot. Also note, neither plot includes the 4% front surface reflection from the substrate.

3.2 IMod Performance

Evaluation of these structures has determined that they do exhibit characteristics which are useful for display applications. Devices have been fabricated with dimensions ranging from 25μm X 25μm to 100μm X 100μm. All active device measurements are made using a PC based modulator test rig for contrast and electro-optic response measurements. This tool utilizes a white light illumination source, and can perform approximate color assessment though not with spectroscopic accuracy. Attributes include the following

Actuation times of < 20μs
Contrast ratio of 5:1 or 10:1 (with or without surface reflection)
Actuation voltages as low as 3volts

In addition, static arrays of IMods have been fabricated for purposes of optical characterization and display evaluation. Static IMod structures are identical to the active devices accept for the fact that a deposited silicon dioxide layer resides where normally an air gap would. The optical response is similar though the difference in the refractive indices of air vs. oxide alters the shape of the reflective peak. Both interferometric "paint chips" and full-color graphical images have been fabricated and characterized. A color model has also been developed to aid in the development of display design.

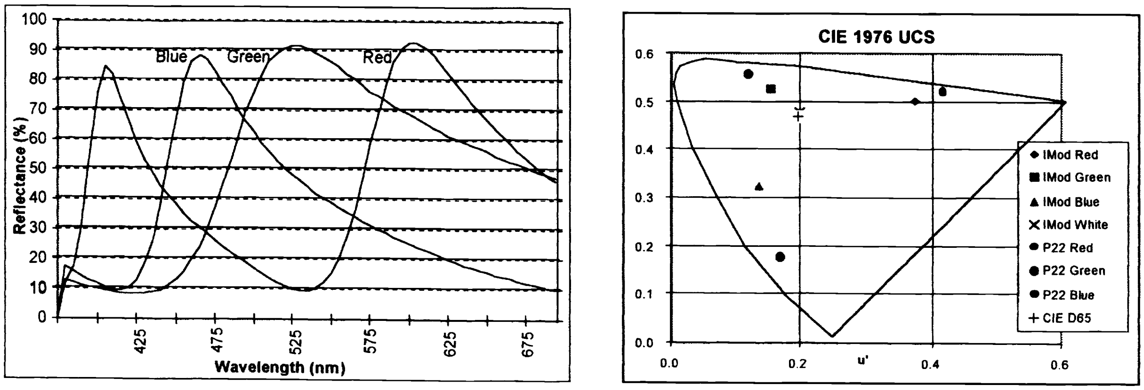

Fig. 5 Spectral Reflectance Functions (SRFs) and associated calculated color gamuts of measured IMod tests at increasing Color/Gap dimensions: green (160 nm), blue (300 nm) and red (400 nm). Color triads are compared to P22 phosphor using CIE 1976 UCS.

The “paint chips” are substrate fragments coated with an IMod structure of a specific thickness. These were fabricated as color components in an RGB triad design optimized for high brightness. The devices were measured using a Cary photospectrometer and the measured SRFs were fed into the color model and compared to the calculations. While the results were good, they were consistently less saturated than the calculated SRFs for reasons not currently well understood. The plots in figure 5 (left) show the measured SRFs which compare favorably to the calculated SRFs shown in Fig. 4. In figure 5 (right), calculated and measured CIE 1976 gamuts of the design are compared to NTSC P22 phosphors. Full color static images show a satisfying level of brightness and saturation and have been well received by potential users.

Efforts were also made to evaluate the white reflectivity of an IMod based display. An 80% active area was assumed. As shown in the table in figure 6, the photopically-weighted white reflectivity (with respect to a MgO standard = 100%) from the spatial white of a measured full color triad increased to 41.8% from a calculated 23.1%.

Design Color	**u’**	**v’**	**L***	**a***	**b***	**% of MgO**
Calc.						
Red	0.39	0.48	44.6	72.8	18.2	14.6%
Green	0.16	0.53	72.3	-41.8	41.1	45.1%
Blue	0.14	0.32	37.0	-0.2	-49.4	9.7%
White	0.20	0.48	54.7	-0.1	4.9	23.1%
Meas.						
Red	0.30	0.48	63.4	52.5	2.3	32.7%
Green	0.18	0.54	84.2	-30.3	59.0	65.7%
Blue	0.16	0.39	58.4	-1.4	-37.8	27.0%
White	0.21	0.48	70.1	4.1	7.1	41.8%

Fig. 6 White reflectivity and CIE L*A*B* coordinates of calculated and measured IMod color display design.

From an electromechanical perspective, the IMod has also performed within theoretical limits. Figure 7 shows a plot of both measured and theoretical electromechanical hysteresis for an IMod with structural dimensions of 40μm X 30μm, a membrane thickness of 200nm, and an undriven air gap value of 180nm. The data indicates that the theoretical and measured responses coincide quite well. The loop itself is relatively wide and the actuation voltages quite low, making the device well suited for a display application.

Initial efforts have also begun to evaluate the expected lifetimes of these devices. Primary reliability issues stem from work hardening phenomena in metals and stress driven fatigue at the supports for the membrane. While a rigorous study has yet to be performed, initial data indicate no degradation in performance in up to 7.5 X 10^{10} actuation cycles. This number is already sufficient for certain low-resolution display applications requiring low refresh rates and grayscales.

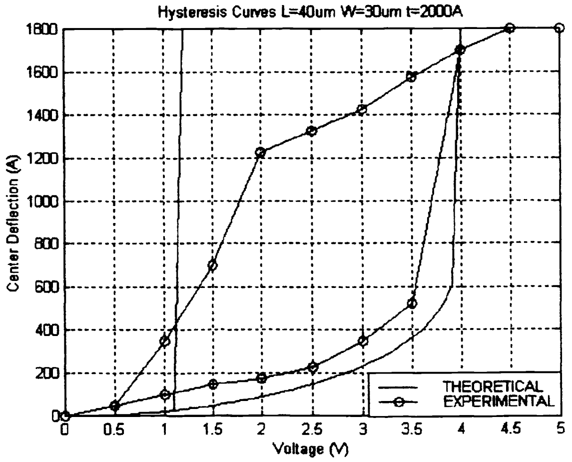

Fig. 7 Theoretical and measured electromechanical response of an IMod measuring 40μm X 30μm. The data coincide well with the expected behavior.

4. DISPLAY APPLICATIONS

The strengths of the IMod as it currently exists lie in several areas. The inherent functionality of the device which incorporates modulation, color selection, and hysteresis. The relatively high brightness and contrast using ambient illumination. Additionally, the exceptionally low drive voltages which, while obtained at the sacrifice of actuation speed, facilitate exceptionally low power consumption. Figure 8 illustrates the display design for which the IMod is being developed. The concept centers around an array fabricated with three sets of IMods optimized to switch between red and black, green and black, and blue and black. The display is driven using conventional digital drivers and addressing schemes, and brightness and color content are controlled by a variation of pulse width modulation. One essential component shown in this diagram is the diffuser film which is attached to the viewing surface of the substrate. This film not only reduces glare from a normally specular surface, but can also enhance the reflectivity cones by creating a "sweet spot".

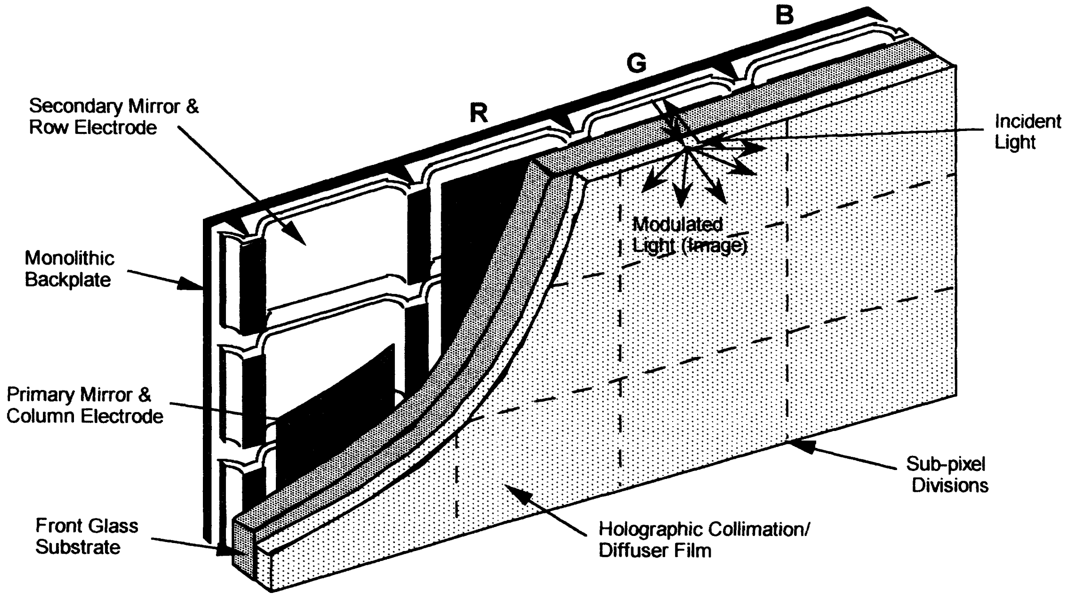

Fig. 8 Design concept for an IMod based reflective display. Full color operation is achieved in a spatial fashion by combining three sets of IMod structures optimized for red/black, green/black, and blue/black switching. The display is digital in operation and should exhibit very low power consumption.

In general, for a modulator to function as the basis of a display, it must incorporate a number of characteristics that include sufficient contrast and brightness, adequate speed, lifetimes and ruggedness commensurate with the display application, and some form of memory or non-linearity inherent to it or otherwise incorporated. When used in a reflective display, the requirements for good contrast are increased and exacerbated by the need to make efficient utilization of incident or supplemental light. The characteristics exhibited by the IMod to date suggest that it can provide a strong basis for display applications which can be described as having medium to low resolution and gray scale requirements. This kind of performance is typified by the increasing numbers of Palm Pilot like handheld devices. Modeling indicates that significant increases in actuation speeds are possible and thus a growth path exists for higher bandwidth applications. In addition, designs are currently under investigation which are capable of providing true black and white and enhanced color performance. This exploration is occurring in conjunction with efforts to realize large-scale manufacturability. Thus the IMod would appear to be well positioned to join the ranks of other MEM modulators which are already contributing to the field of displays.

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