Interferometric Modulation: A MEMS Based Technology for the Modulation of Light

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Abstract

Interferometric Modulators™ (IMods™) are a class of micromachined, deformable optical cavities whose reflected or transmitted color changes with the application of a voltage. Exhibiting switching speeds > 50 KHz and prominent hysteresis, these devices show much promise for a variety of applications ranging from reflective FPDs and projection systems to color printers. Their development status will be presented, and their application to reflective FPDs will be discussed.

Introduction

Many imaging and consumer electronics products have, as a key component, a light modulator. For consumer electronics this generally manifests itself in the form of a FPD of one kind or another. In imaging systems these modulators include single, linear, as well as two-dimensional arrays of elements. For passive modulators, i.e. devices which do not emit light, LCDs are the predominant technology. However for some applications, like reflective displays, LCDs currently pose limitations, particularly with respect to speed and optical throughput. Displays based on microelectromechanical systems (MEMS) offer the potential to address these issues.

Objective and Background

Display technologies using MEMS have been under development for a number of years now. However it is only recently that this class of devices has begun to make their presence known in the industry. Projection systems based on arrays of movable mirrors have already reached the marketplace(1). Approaches utilizing diffractive arrays(2), and mechanical shutters are in various stages of development. In general, MEM modulators are attractive because of their high speeds, digital behavior, and integrated nature. However, the operating principles of most of these devices, relying on the controlled redirection or diffraction of light, limits their role to applications with fixed viewing angles.

Etalon has developed a new MEM modulator with the potential to address these shortcomings. The device, referred to as an Interferometric Modulator™ (IMod™), relies on the phenomena of interference to alter the color of reflected or transmitted light. A reflective version of the IMod has already exhibited switching speeds of less than 20 µseconds, and programmable color selection. Models indicate the potential for MHz switching, > 80% peak reflectivities, and contrast ratios > 30:1. IMods have inherent memory and thus require only passive matrix addressing. In addition they have extremely low power requirements, potentially enabling VGA displays in the 100 mw range or lower. The unique characteristics of this structure could enable full-color reflective direct view FPDs, with “paper like” performance and video capabilities.

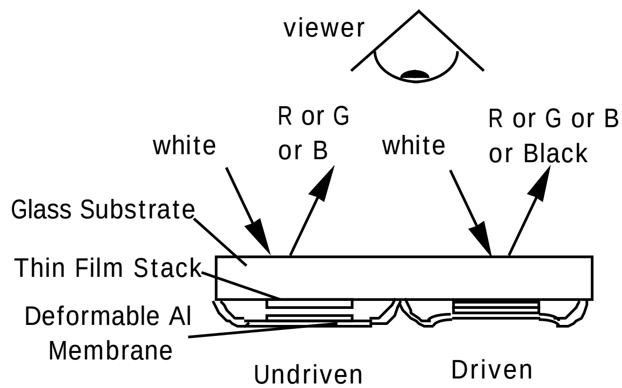

Figure 1 Illustration of the basic structure of a reflective Interferometric Modulator (IMod).

The IMod consists of a self-supporting deformable membrane and a thin film stack, both residing on a transparent substrate, which act as the mirrors of an optically resonant cavity. In this initial design, the deformable membrane is comprised of aluminum and the thin film stack is electrically conducting. Figure 1 illustrates the structure. Both the membrane and the stack have insulating layers. Application of a voltage produces electrostatic forces which cause the membrane to collapse and results in a change in the color of the reflected light. In particular, the reflected color is determined by the distance between the membrane and the stack. Figures 2 and 3 show spectral reflection functions at four different spacings. The design provides a very good black state, calculated to reflect less than 0.6% across the visible spectrum. The membranes are 25 microns square and, depending on the application, would be combined to form subpixel arrays. Active areas are expected to be on the order of 80%.

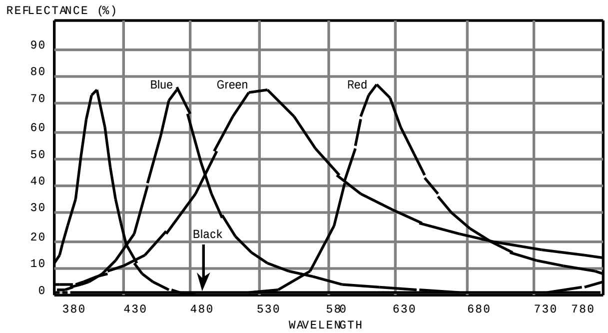

Figure 2 Spectral Reflectance Functions (SRFs) of calculated IMod filter designs at increasing Color/Gap dimensions: black (50 nm), green (160 nm), blue (300 nm), red (400 nm).

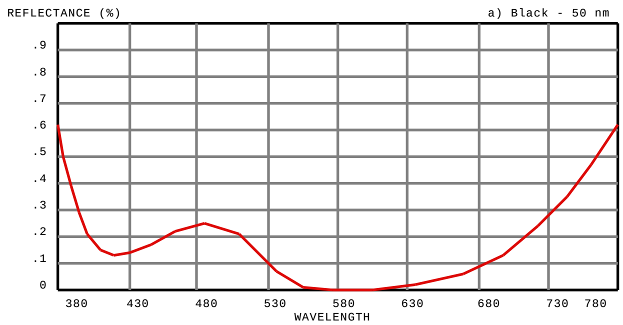

Figure 3 Reduced scale plot of SRF of calculated black Color/Gap dimension.

While continously tunable IMods are possible, a simple display would utilize devices which operate in a binary fashion, switching from one color to another, or from one color to black. The colors are determined by the thickness of the insulating layers, as well as the height of the deformable membrane. For a full-color display, three sets of IMods would be fabricated with dimensions selected to allow red-black, green-black, and blue-black switching respectively. Arranged in spatial RGB stripes, white is achieved by an additive mixture of all three stripes. True black and white displays are possible by combining alternative sets of IMods.

Results

The work to date has resulted in the fabrication and preliminary characterization of small 16 X 16 IMod arrays, as well as the preliminary fabrication of larger arrays (300 X 330) on glass substrates (Corning 7059F) which are 2” square. Each array is driven as a single pixel, and is observed with a conventional microscope using reflected white light. The IMods are viewed through the substrate. This generation of devices is fabricated without an integral black mask which will be included in subsequent designs. Consequently, much stray light was reflected from the inactive areas between individual IMods as well as spurious light from the supports and the periphery of the membrane. However this does not preclude the collection of fundamental operational data.

Switching voltage for the current devices is approximately 15 volts, with a 30 volt DC bias applied. Drive voltage is dependent upon the mechanical properties of the membrane, i.e. material thickness and residual stress. Charge migration through the insulators also plays a role by increasing the voltage required to fully actuate the device. Drive voltages are expected to decrease as device parameters are optimized. Enhancing the quality of the insulators and conductors should further reduce required voltages.

Switching speeds are currently measured using a silicon photodetector located near the focal plane of the microscope eyepiece. This is a characteristic which is also primarily determined by the mechanical characteristics of the membrane. IMods to date have exhibited switching speeds exceeding 50 KHz (< 20 µsec response), though electromechanical modeling of the device indicates that multi-MHz speeds are attainable. Insulator/conductor quality and residual membrane stress both contribute to this disparity.

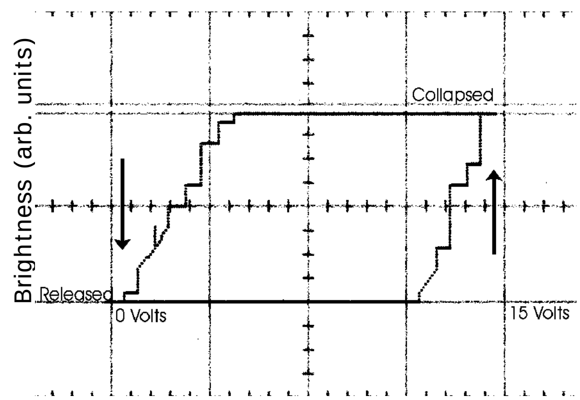

Figure 4 Plot of drive voltage vs. output magnitude revealing hysteresis of the IMod.

Hysteresis has also been measured with these structures. Figure 4 shows a plot of reflected light magnitude vs. applied voltage. The result clearly illustrates the inherent electromechanical memory associated with such structures. Drive voltage in this case was a 50 KHz sawtooth wave with an amplitude of 15 volts, and a bias of 30 volts. Gray scale would be achieved by pulse width modulation (PWM), exploiting the IMod’s high speed and inherent memory.

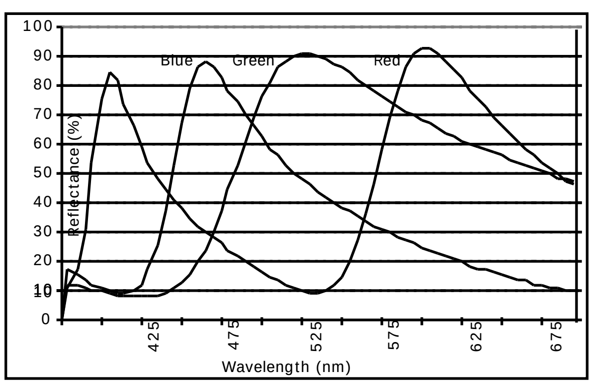

Figure 5 Spectral Reflectance Functions (SRFs) of measured IMod tests at increasing Color/Gap dimensions: green (160 nm), blue (300 nm) and red (400 nm).

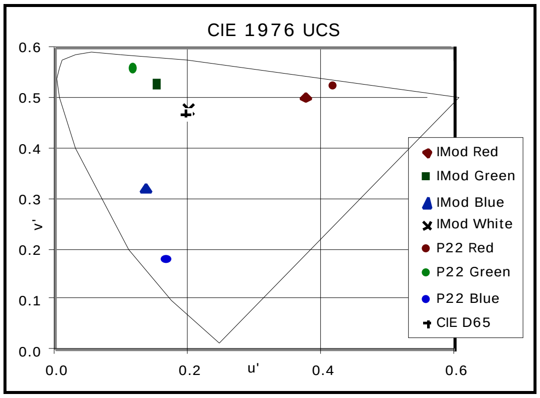

Figure 6 Calculated color gamuts of IMod color display triads compared to P22 phosphorsusing CIE 1976 UCS.

Static arrays of IMods have also 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 airgap 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.

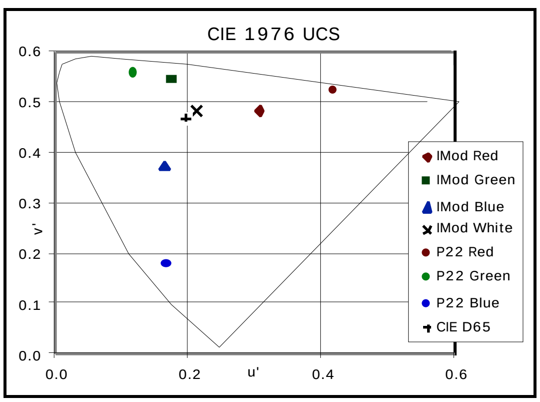

Figure 7 Measured color gamuts of IMod color display triads compared to P22 phosphorsusing CIE 1976 UCS.

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 graphs in figure 5 show the measured SRFs which correspond to the calculated SRFs shown in Figure 2. In figures 6 and 7 respectively, 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 8 below, 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%

*Figure 8 White reflectivity and CIE L*A*B* coordinates of calculated and measured IMod color display design.*

Transmissive IMods

The ability to utilize a wide variety of structural and optical materials makes possible the fabrication of IMod designs with many different modulation functions. Some applications, color printing for example, may be better served by a device which acts in transmission mode. One such design is illustrated in figure 9, which shows a spectral transmissive function (STF) for a calculated IMod design. The basic mechanical structure of the IMod remains the same. However, a different set of thin films is used in the construction of the device. The result is a transmissive device optimized for green, with a peak transmission of > 80%. This design should exhibit similar speed and hysteresis characteristics.

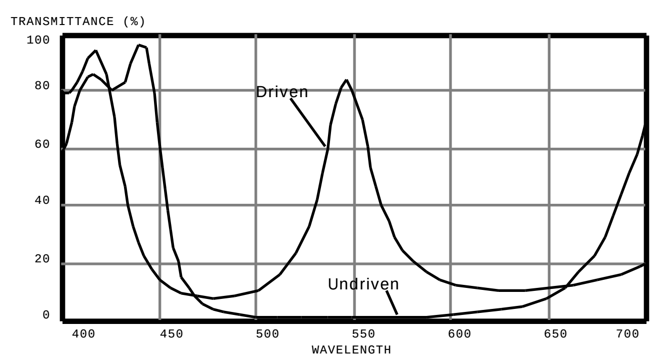

Figure 9 STF for a transmissive IMod design showing Driven and Undriven states.

Impact

We have demonstrated a new technology for light modulation, and a powerful basis for the fabrication of MEMS based flat panel displays. Full characterization of the IMod and further optimization of its operation and fabrication process are underway. In addition, the process must be modified to incorporate a black mask (for FPDs). However the data obtained so far are quite promising, and satisfy the basic requirements for an IMod based display. In addition, a design has been established for a full color display that compares favorably with the color reflective LCD development results presented recently. From a display application standpoint, IMods are suitable for both projection and direct view displays. Furthermore, the inherent simplicity of the structure and process suggests a rapid manufacturing learning curve. In general, the IMod would appear to provide a clear path to implement full-color and video speeds over wide temperature ranges at a cost structure considerably less than that of AMLCDs.

Acknowledgements

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