Electron-beam-addressed membrane mirror light modulator for projection display

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The performance of a prototype, reflection-mode projection display based on an electron-beam-addressed membrane mirror light modulator (e-MLM) is described. The e-MLM converts electronic video information into a two-dimensional phase object, that is then schlieren imaged onto a screen. High-contrast dynamic projection of images is demonstrated over a broad range of wavelengths, from the visible to the midinfrared. As such this device is expected to find applications in large-screen visible displays and dynamic infrared scene projectors.

Key words: Deformable mirror, spatial light modulator, infrared scene projector, high-definition display.

1. Introduction

Since the work of Preston, the membrane light modulator (MLM), which incorporates a deformable membrane mirror as the light modulating element, has emerged as an attractive technology for adaptive optics, projection display, and optical signal processing applications. MLM’s exhibit fast response times, can be read out with high optical efficiency, and may contain a large number of resolution elements.

Various means of addressing a two-dimensional deformable membrane have been demonstrated, including electron-beam addressing, optical addressing, and electrical addressing by means of integrated circuits. The construction of an MLM is such that a membrane is deposited over an array of recessed wells with an addressable electrode at the bottom of each well. The exterior surface of the membrane is coated with a highly reflective, conductive material that is biased by a programmable voltage source.

A pixel, which may span one or more wells, is activated by establishing a potential difference between the corresponding well electrode and the membrane surface, which causes the membrane to deform into the well in response to electrostatic forces. By the application of a spatially varying pattern of voltages to the array of well electrodes, a two-dimensional pattern of phase retardation is presented to an incoming optical wave front. This phase modulation of the reflected readout light can be converted to intensity modulation by the schlieren technique and projected onto a screen.

Because of the broadband reflectance of the mirror surface, this technology is suitable for both ultraviolet and IR scene projection, as required by hardware-in-the-loop target simulators. The combination of high reflectance and high optical readout efficiency also makes possible large-screen displays, as well as projectors for wide field-of-view flight simulators.

2. Description and Operating Principles of the e-MLM

A. Device Architecture

The electron-beam-addressed membrane mirror light modulator (e-MLM), which is illustrated in Fig. 1, consists of an addressing electron gun and a special deformable membrane mirror anode assembly. This anode assembly consists of a planar grid and a charge-transfer plate (CTP) to which a deformable membrane mirror is bonded. The mirror material is...
chosen for its high reflectivity in the wavelength band of interest.

The CTP is a wafer of electrically insulating material embedded with a dense, regular array of conductive pins precisely oriented normal to the wafer surface, in a hexagonal array.\textsuperscript{13} The CTP derives its name from its ability to serve as a high-density, multifeedthrough vacuum interface that is capable of transferring a two-dimensional charge distribution from vacuum to air. Our laboratories produce 25-mm-diameter, 4-mm-thick CTP's with 10-\mum conduc-
tors on 14-\mum centers, 25-\mum conductors on 35-\mum centers, and 50-\mum conductors on 70-\mum centers. The resulting surface area fill factor of these close-
packed arrays is approximately 50%. A photomicro-
ograph of a CTP surface with 25-\mum pins is shown in Fig. 2.

In one version of the device, the CTP is polished to yield an optically flat surface, and material is removed from the pins on one side of the plate so as to form a regular array of recessed wells. We have also fabri-
cated devices by using photomask and etching tech-
niques to deposit an array of wells directly onto the CTP surface such that the wells are oversampled by the CTP pins, as depicted in Fig. 1. In this manner the depth of the wells, the pixel diameter, and both the fill factor and the symmetry of the array can be chosen according to the wavelength of the light to be processed and the specific system function of the spatial light modulator (SLM). A polymeric mem-
brane is then deposited over the wells such that a reliable bond between the two dielectric surfaces is established by van der Waals forces.

B. Electronic-Beam Addressing

Electrostatically, the e-MLM may be viewed as a triode consisting of a cathode biased at $V_\text{k}$, a collector grid at $V = 0$, and an anode (CTP surface) referenced to the membrane potential $V_m(t)$. The thermionic cathode at $V_\text{k} < V_m(t) < 0$ emits a primary electron beam that strikes one or more pins of the CTP. The local potential of the CTP, which determines the landing energy $E_p$ of the primaries, is initially close to $V_m(t)$. $E_p$ is given by

$$E_p = e(V_\text{k} - V_\text{s}),$$

where $e$ is the electronic charge and $V_\text{s}$ is the local potential of the anode surface being addressed. When the device is initially in its uncharged state, $V_\text{s} = V_m$, while, in general, $V_m < V_\text{s} < 0$ when image information is being written. The ratio of emitted secondary electrons\textsuperscript{14} to primary electrons incident on the CTP surface, which is defined as $\delta$, is also determined by $E_p$. The value of $\delta$ strongly influences the efficiency with which pixels can be charged, and so affects the maximum framing speed of the device.

When the CTP is uncharged, essentially all the voltage applied to the membrane surface is coupled by capacitive division across the gap between the CTP and collector grid. Since there is no potential difference across the pixel, the membrane remains in its undeformed state. As the electron beam scans across a conductive pin of the CTP, secondary electrons are emitted from that pin so that the accumulated charge establishes a potential difference between the CTP and the grid. If the value of $E_p$ is such that $\delta$ exceeds unity and the pin is at a lower potential than the collector grid, a net positive charge accumulates on the pin. If the electron beam continues to address that pin, charge accumulates until the pin potential stabilizes to the grid potential, i.e., to ground.

C. Framed Operating Mode

In the framed mode of operation, a negative dc bias is applied to the membrane and the electron beam is rastered across the anode while the value of its current is modulated by the video signal applied to the cathode control grid. This achieves gray scale in the manner of cathode-ray tubes\textsuperscript{15} (CRT's). The beam current can be limited such that no anode pixel is allowed to saturate to the grid potential during one
video frame. Since the resulting potential of each addressed pixel is simply proportional to the beam current at that pixel, a continuously varying two-dimensional charge image can be written onto the anode.

The anode's large (~1 pF) pixel capacitance, and hence a long (minutes) charge storage time, requires that the image be erased between frames. Erasure is easily accomplished by grounding the membrane electrode during electron-beam addressing. Setting the membrane potential equal to the collector grid potential switches all pixels charged with image information to a more positive potential than that of the collector. Since a large fraction of the secondaries emitted from these pins cannot overcome the repulsive field between the anode and collector, they fall back to the anode and neutralize the net positive charge, erasing the image. A simple means of incorporating an explicit erase cycle is by utilizing an RS-170 format such that the image is erased during the second field of each frame; this, however, reduces the duty cycle of the projector to < 50% and results in image flicker. This duty cycle can be greatly increased by instead flooding the anode with a defocused beam of electrons for an erase time that is much less than a field period. We have shown that this approach can decrease the required erase time by an order of magnitude and increase the duty cycle to almost 90%. Replacing the raster by a flood erase takes advantage of the large parallel capacitance of the CTP,16 i.e., driving them to ground in parallel requires much less total charge than driving them to ground serially.

The frame address or write time \( \tau_w \) of the e-MLM is given by

\[
\tau_w = \frac{NCV}{ip(\delta - 1)T},
\]

where \( n \) is the number of pixels in the array, \( C \) is the pixel capacitance, \( V \) is the potential difference required for deflecting the membrane field to full-contrast modulation, \( ip \) is the primary electron current assumed to be confined within a pixel, \( \delta \) is the secondary electron emission ratio of the CTP, and \( T \) is the collector grid transmission. The beam current-limited frame rate \( R \) is given by

\[
R = (\tau_e + \tau_w)^{-1},
\]

where \( \tau_e \) is required frame erase time, and \( \tau_e \leq \tau_w \).

D. Flickerless Operating Mode

The flickerless operating mode also is achieved by choosing \( E_s \) such that \( \delta > 1 \), but the negative-going video signal is applied directly to the membrane surface rather than to the control grid of the electron gun.17 In this case, if the pin voltage is below the collector potential, secondary electrons generated at the pin are collected by the grid, and the pin voltage increases. Similarly, if the potential of the pin is above that of the collector, secondary electrons emitted from the pin are returned by the electric field between the pin and collector so that the pin voltage falls as electrons are deposited. Thus, in this mode, which is termed the grid-stabilized mode, the voltage at the pin that is being addressed by the electron beam always tends toward the collector potential. By synchronizing the video signal with a constant-current raster address of the anode by the electron beam, an arbitrary charge image can be written onto the CTP. Given sufficient beam current, the potential between the membrane and well electrode is thus simply equal to the instantaneous video signal. Also, the charge-storage characteristics of the CTP result in image information being maintained between frames. Previous frames are simply updated on a pixel-by-pixel basis as the electron beam scans the anode to write new frames. Since an explicit erase cycle is not required, flickerless operation is achieved. We note that during the process of grid stabilization the grid ceases to act as an efficient collector of secondaries as the pin potential approaches the grid potential. Thus landing errors of emitted secondaries onto neighboring pins can degrade spatial resolution and reduce image contrast. Fortunately this problem can be alleviated by spacing the collector mesh within a pixel pitch of the anode surface; this ensures that returning secondaries (except those emitted at large angles from the surface normal) land close to the addressed pixel.

E. Speed of Operation

One of the attractive attributes of the MLM technology is its fast response time,16 which makes high frame rates possible. In the e-MLM, the limiting factor in determining frame rate is the beam current of the addressing electron gun. For example, since the flickerless grid-stabilized mode requires about half the beam current as the framed mode of addressing, it can support twice the update (or frame) rate. By manipulation of Eq. (2), a lower limit to the effective frame rate may be expressed as the throughput \( Q \) of the e-MLM for grid-stabilized operation:

\[
Q = \frac{N}{\tau_w} = \frac{ip(\delta - 1)T}{CV},
\]

where \( Q \) may be expressed in pixels/s. Given the following device-dependent parameter values that are consistent with empirical studies, i.e., \( V = 50 \) V, \( \delta = 1.5, C = 0.5 \) pF, \( ip = 250 \) µA, \( T = 0.8 \) yields \( Q = 4 \times 10^6 \) pixels/s. While a reduction in pixel capacitance \( C \) would result in increased speed, we also note that a substantial increase in the delivered beam current may be effected by replacing our present vidicon tube technology by dispenser cathode, laminar-flow-based diode guns such as those incorporated in high-output projection CRT's.18,19 In addition, for IR displays that permit larger pixel dimensions, a larger beam spot is acceptable. This relaxes the space charge effects that fundamentally limit the current density at the target, resulting in a higher delivered current and, hence, a higher throughput.
F. Image Formation

The voltage pattern capacitively written onto the MLM anode is converted to a phase object by the deformation of the reflective membrane into the pixel wells. As the readout light is reflected from the membrane surface, the light is also diffracted into discrete orders because of the periodicity of the close-packed pixel array of the modulator surface. With the e-MLM in its off state, the mirror surface is undeformed, and only the specular, or zeroth-order, reflection contributes to the diffracted wave. Diffraction into the higher orders increases as the pixels are activated. The phase-modulated readout beam can be Fourier transformed by a lens to produce a diffraction pattern consisting of an array of bright spots with the sixfold symmetry of the hexagonal pixel array. Thus, in a Fourier plane, the diffracted orders provide spatial carrier frequencies for phase information. Being separated in space, they can be spatially filtered such that any combination of orders are passed and the others blocked. The passed diffraction order(s) then creates an intensity-modulated image of the phase object at the image plane. This is equivalent to the technique of schlieren imaging.

Figure 3 illustrates the optical train of the schlieren projector. One form of Fourier-plane spatial filtering, the zeroth-order stop, is illustrated. The results described below may be compared with a similar analysis for the case of rectangularly shaped pixels described previously.

Figure 4 depicts a cross-sectional view of a single pixel of diameter $a$, in which an applied voltage across the air gap has deflected the membrane a maximum distance $d_0$ into the well. The shape of the deflected membrane may be modeled as a circularly symmetric paraboloid, so that the deflection as a function of position is given by

$$p(x, y) = \begin{cases} d_0(4x^2 + y^2)/a^2 - 1, & \text{if } x^2 + y^2 \leq a^2/4 \\ 0, & \text{otherwise}, \end{cases}$$

where the $x$ and $y$ axes are in the plane of the undeflected membrane surface and the coordinate system's origin lies at the center of the pixel.

We consider the case in which all pixels are deflected to the same positions. The deflection function, ignoring for the moment the finite aperture of the e-MLM, can be written as

$$d(x, y) = p(x, y) \ast \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \delta \left( x - \frac{c}{2} (k + l), y - \frac{\sqrt{3}c}{2} (k - l) \right),$$

where $c$ is the center-to-center spacing of the pixels, $k$ and $l$ are integers, and $\ast$ denotes the convolution operation. The double summation in Eq. (6) defines a hexagonal array of impulses located at the pixel centers. The corresponding phase-delay function, which is seen by an incident monochromatic wave front of wavelength $\lambda$, is

$$\phi(x, y) = \frac{4\pi}{\lambda} d(x, y).$$

For a device of diameter $D$, the function

$$s(x, y) = \begin{cases} 1, & \text{if } x^2 + y^2 \leq D^2/4 \\ 0, & \text{otherwise}, \end{cases}$$

defines the active area aperture. If the membrane is assumed to have a uniform reflectance of 1 across its surface, then, within a constant phase term, an incident wave front is multiplied by the complex theoretical diffraction efficiencies and contrast ratios for various pixel geometries and Fourier-filtering schemes. The results described below may be compared with a similar analysis for the case of rectangularly shaped pixels described previously.

III. Device Modeling

A. Diffraction Efficiency for a Uniformly Deflected Two-Dimensional Array of Pixels

We have modeled the complex transfer function of the pixelized membrane surface in order to determine...
function
\[ m(x, y) = s(x, y) \exp[j\phi(x, y)] \]  \hspace{1cm} (9)

after reflection.

It is desirable to determine the optical Fourier transform of \( m(x, y) \) to evaluate diffraction efficiency, contrast ratio, and other performance parameters. Unfortunately the transform does not have a simple analytic form. Instead we calculate the Fourier transform numerically for a range of pixel fill factors and the membrane deflections.

For the purpose of computing its discrete Fourier transform, \( m(x, y) \) was sampled on a hexagonal grid, and a linear coordinate transformation was used to align the hexagonal grid of samples onto a rectangular grid:
\[ x' = x, \]  \hspace{1cm} (10)
\[ y' = y/\sqrt{3}. \]  \hspace{1cm} (11)

Figure 5 shows how application of this coordinate transformation aligns the centers of the pixels onto a rectangular grid. The inverse transformation is applied to the discrete Fourier-transform result to restore hexagonal symmetry.

In Fig. 5, a dotted rectangle demarcates the unit cell, which is the smallest cell that can be replicated along the \( x \) and \( y \) axes to produce a hexagonal grid of pixels. In the right-hand figure of Fig. 5, the unit cell can be sampled on a square grid to give a discretized function \( u(m, n) \). The discrete Fourier transform of \( u(m, n) \), which is denoted by \( U[k, l] \), when convolved with the continuous Fourier transform of the aperture function \( s(x, y) \) gives \( M(u, v) \), which is the continuous Fourier transform of \( m(x, y) \). \( M(u, v) \) has the form of a hexagonal array of impulse-like intensity peaks [see Fig. 6(a)]. For the optical Fourier transform taken by a nonbandwidth-limiting lens of focal length \( f \), the spacing and width of peaks is as shown in Fig. 6(b). As long as the device aperture is much larger than the spacing between adjacent pixels (\( D >> c \)), \( M(u, v) \) will be a nearly hexagonal array of impulses. In this case one can consider \( M(u, v) \) as a set of discrete diffracted orders in which the energy in each order is the squared magnitude of the corresponding entry of \( U[k, l] \).

B. Dependence of Intensity and Contrast on the Pixel Fill Factor

The above model was used to calculate the fraction of energy in an incident plane wave that is diffracted into the central (zeroth) order as a function of membrane deflection. Deflection is normalized to units of wavelengths and is measured at the center of the pixel. \( U[k, l] \) and \( u(m, n) \) were sampled on a grid of \( M \times N \) grids, and the fraction of zero-order energy, \( I_0 \), was calculated as
\[ I_0 = \frac{M-1 \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} |U(k, l)|^2}{M-1 \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} |U(k, l)|^2}. \]  \hspace{1cm} (12)
Figure 7 shows the results expressed as a percentage of the total energy. Several curves are plotted for different pixel spacing–pixel diameter \((c/a)\) ratios. The fill factor, which is defined as the fraction of the device active area covered by pixels, is related to \(c/a\) by

\[
\text{fill factor} = 0.907/(c/a)^2.
\] (13)

It can be seen from Fig. 7 that as \(c/a\) approaches 1.0, it is possible to diffract a greater fraction of the light out of the zero order. The curves of Fig. 7 may be used to determine a theoretical upper limit on the contrast ratio of an e-MLM imaging system that passes only the zero order at the Fourier plane by taking the ratio of the maximum (always 1.0) to the minimum values along the curve corresponding to the device's fill factor. For this device, the lower the \(c/a\) ratio, the better the contrast ratio. For \(c/a = 1.03\), the theoretical contrast ratio is 150:1.

Figure 8 is a similar plot, but it shows the sum of the energy diffracted into the six first-order peaks closest to the zeroth order. For an e-MLM imaging system passing only these orders, maximum light throughput is reduced to less than 60%, but there is no theoretical limit on the contrast ratio since an undeflected membrane diffracts zero energy into the first order.

Once the Fourier transform is calculated, we may simulate the spatial filtering that yields contrast in the image plane. For example, we may set the dc component of the Fourier transform \(U[0, 0]\) to zero, which simulates the effect of incorporating the zeroth-order stop of Fig. 3. Inverse transforming the filtered Fourier transform and taking the squared magnitude of the result then reconstructs what one would see in the image plane. For purposes of illustration, Fig. 9 shows six samples of the image plane for a uniformly deflected array of pixels with deflections \(d_0\) for \(0.1\lambda \leq d_0 \leq 0.7\lambda\). The assumed pixel fill factor was 40%. The assumptions of a perfectly coherent, monochromatic light source and a parabolic deformation profile yield interference effects that result in circular rings within the pixels for \(d_0 > 0.3\lambda\). The extent to which these coherent artifacts would be present in a real display depends on the spectral bandwidth and spatial coherence of the light source, and on the fidelity of the imaging system. In any case, the display would typically be operated only within the range \(0 \leq d_0 \leq 0.3\lambda\), since this range covers the device's full range of gray-scale modulation.

C. Assumptions

This analysis makes the assumptions that pixels experience paraboloidal deflection under an applied voltage, and that the pixel diameter is large compared with the wavelength used but small compared with the diameter of the device's total active area. We also assume that the Fourier-transform lens has an aperture that is large enough so that all diffracted orders are collected. Another significant assum-
An electronic controller generated the input signals system that incorporated a 256 x 256 frame buffer, the control electronics included a vector address to the e-MLM. For the first demountable prototype, B. Control Electronics with a ribbon filament emitter to make it vacuum static raster, Teltron Model 1301 vidicon gun fitted we replaced it with a high-resolution, low energy requirements when operated at low beam energies, density delivered by this gun were insufficient for our and a beam diameter of < 150 μm at a beam energy of 200 eV. The gun reliably produced a current of 250 nA and a beam diameter of < 150 μm at a beam energy of 300 eV. Since the spatial resolution and current density delivered by this gun were insufficient for our requirements when operated at low beam energies, we replaced it with a high-resolution, low energy vidicon gun. The unit was a magnetic-focus, electrostatic raster, Teltron Model 1301 vidicon gun fitted with a ribbon filament emitter to make it vacuum demountable. The gun delivered 2 μA of beam current in a 70-μm spot at 200 eV.

B. Control Electronics

An electronic controller generated the input signals to the e-MLM. For the first demountable prototype, the control electronics included a vector address system that incorporated a 256 x 256 frame buffer, an optoisolated digital–analog converter interface, and three high-voltage amplifiers. The user interface was an IBM personal computer that permitted the user to specify the image information to be displayed by the projector. The image information consisted of three 128 × 128 arrays that defined the x, y position and z (intensity) values assigned to each element of the image array. Once defined, the image information was serially output by the frame buffer to three separate digital–analog converters, and amplified to drive the x, y electrostatic deflectors and z control grid of the electron gun. The outputs were able to modulate the voltage applied to the video grid with a resolution of 8 bits. Once the higher-performance vidicon gun was incorporated into the test system, the vector control electronics were also replaced by custom video electronics that accepted an RS-170 input. This input was supplied by either a frame grabber (for static images) or a video cassette recorder (for dynamic images). Our initial mode of addressing was a framed mode, in which the voltage applied to the membrane was controlled by the vertical retrace signals so that a separately variable (but integral) number of fields could be used for the write and erase cycles. It was found that a 3:1 ratio between the write and erase dwells gave good performance without excessive flicker, albeit at an overall frame rate of 15 Hz. Nonstandard video rates would be required for a 30-Hz operation with unequal write and erase times. Since the flickerless address mode does not require an erase cycle, 30-Hz video rates can be maintained while also simplifying the control electronics and reducing the beam current requirements of the electron gun. We now implement this mode of addressing in our video-rate display systems.

C. Projector Performance Characteristics: Coherent Visible Readout

Over the course of its development the e-MLM was read out by both coherent and incoherent light sources. Figure 10 illustrates the image plane irradiance of a typical 50-μm pixel within a group of uniformly deflected pixels, read out by a He–Ne laser at a wavelength of 632.8 nm. The data were obtained by passing only the zeroth order in the Fourier plane, and the photodetector was apertured during the measurement to define the pixel. A contrast ratio of greater than 100:1 was recorded within this pixel. The active fill factor of this device was ~ 70%. Figure 11 shows the corresponding modeled intensity versus deflection but for an ensemble of uniformly deflected pixels of a 70% fill device, similar to the solid curve of Fig. 7, extended to 8π of phase shift. By comparing the curve of Fig. 11 with the data of Fig. 10, membrane deflection as a function of bias voltage may be determined as shown in Fig. 12. It can be shown6 that the membrane deflects
according to the relation

$$d_0 = \frac{a^2 \epsilon_0 V^2}{32T s^2},$$

(14)

where $d_0$ is the amplitude of membrane deflection, $a$ is the pixel diameter, $V$ is the operating voltage, $T$ is the membrane tension, $s$ is the well depth, and $\epsilon_0$ is the permittivity of free space.

While visual comparison of Figs. 10 and 11 indicates good agreement between their lineshapes, it is evident from Fig. 12 that the deflection sensitivity of the membrane decreases with the applied voltage so that it ceases to be quadratic for displacements greater than $\approx 0.4 \mu m$. Although the reasons for this behavior are not known at present, we note that, if $T$ were to increase nonlinearly with $d_0$, it would certainly reduce the voltage sensitivity of Eq. (14) for large values of $d_0$.

D. IR Readout Characteristics

This device was also read out in the IR (see Ref. 25) by replacing the visible laser with a 4-mW He–Ne laser operating at 3.39 μm, followed by an IR-transmissive beam expander and projection optics; the visible input window of the e-MLM was also replaced by a demountable ZnSe window. Figure 13 shows an image of a girl’s face produced by this system by using a zeroth-order schlieren readout at a mirror bias of 220 V. The 128 × 128 input image was written onto the MLM anode by the vector-addressed Apex Electronics electron gun. The picture was obtained by photographing the CRT display of an Inframetrics 600 self-scanning HgCdTe video camera, which we used as an imaging radiometer. The radiometer indicated that the simulated temperature range of the projected image was 200°C.

Encouraged by the initial IR performance, we
proceeded to modify the pixel array dimensions to increase the phase dynamic range of the e-MLM for IR scene projection. While, for visible displays, the 50-μm diameter CTP pins themselves could be used to fabricate the mirror pixels by etching away a few micrometers of the pin material to form individual wells, this was not adequate for a much longer wavelength readout, so the diameter of the pixels was increased. This requirement stems from the fact that avoiding collapse of the membrane requires that the pixel well depth s be at least three times the maximum mirror deflection. Moreover, Eq. (14) indicates that, for a given pixel diameter, the operating voltage V scales linearly with the well depth and as the square root of the deflection amplitude, i.e., \( V \propto \sqrt{sd} \). This results in unacceptably high operating voltages for 50-μm pixels with wells that are deep enough to accommodate midwave IR or long-wave IR radiation. For example, since a deflection of \( d_0 \leq \lambda/3 \) is sufficient for gray-scale image modulation, one could argue that \( s \geq \lambda \) is a reasonable limiting design parameter. For a fixed pixel diameter, then, the operating voltage V for a device optimized to modulate the light of wavelength λ may then be scaled from the known operating voltage \( V_0 \) of a device optimized to modulate the light of wavelength \( \lambda_0 \) by the relation \( V = V_0 (\lambda/\lambda_0)^{3/2} \). Since the device of Fig. 10 incorporated pixels with a 3-μm well, it follows that a 12-μm well device of the same diameter built to modulate light in the 8–12-μm band would require 8 times the mirror bias.

Several e-MLM anodes were produced for our demountable midwave IR test system, which featured a 10-μm well depth, with 159-μm diameter pixels on 214-μm centers in a hexagonal array; the pixel fill factor was 50%. The pixel arrays were fabricated directly on the polished CTP surface by using a photolithographic process. Figure 14 shows the zeroth-order optical readout intensity versus the mirror bias for this device. The crosses represent measured data, while the solid curve is the behavior predicted by the model of Section 3. The two should be directly comparable, since the data were collected with a large-area cooled PbSe photodetector positioned in the image plane, which averaged the combined signal from a group of 6 pixels within a large array of uniformly deflected pixels. Figure 15 shows similar data and theory for a dark-ground filtering technique of a zeroth-order stop. The modeled curve represents the addition of the first through fourth diffraction orders, since we calculate that the clear aperture of our projection lens was such that only these orders were collected by the lens. The scale of the ordinate is normalized to the image plane intensity obtained by inserting a mirror in place of the SLM, and removing the Fourier-plane filter. The 75% peak irradiance level at 160 V is thus the optical efficiency of the SLM at this wavelength. This number can be increased by enlarging the numerical aperture of the projection lens so that a greater number of diffraction orders are collected. In practice some losses are also expected because of surface reflections from the refractive optics, and finite absorption by the lens material. These losses are partly responsible for the peak amplitudes of the theoretical curves of Figs. 14 and 15 being larger than those of the measured data.

Figure 15 demonstrates both the gray scale and the dynamic range of the device. Contrast ratio, which is defined as the ratio of maximum to minimum intensity, was about 130:1 after subtracting a background irradiance measured with the commercial mirror in place; we attribute this background to scattering from the uncoated projection lens. This background represents ~30% of the overall off-state signal, and the remainder is presumably due to the SLM. A maximum deflection of >2 μm was attained, which is sufficient to modulate an 8-μm readout light.

Fig. 14. Image plane intensity versus mirror bias for an e-MLM incorporating 159-μm-diameter pixels at a readout wavelength of 3.39 μm. The device was read out by passing the zeroth order in the Fourier plane. The scale of the ordinate has been normalized to the throughput of the optical train. Crosses, measured data; curve, theoretical model.

Fig. 15. Measured and theoretical intensities analogous to those of Fig. 14, but read out with the zeroth-order stop illustrated in Fig. 3. The scale of the ordinate has been normalized to the throughput of the optical train so that the peak intensity of 75% is the optical readout efficiency of the SLM. Crosses, measured data; curve, modeled intensity of the sum of the first four nonzero orders.
E. Sealed-Tube e-MLM: Broadband Incoherent Readout

Having successfully determined many of the required operating parameters for the vacuum-demountable e-MLM, we proceeded to move toward a commercially attractive version that incorporated state-of-the-art camera tube technology. Working in collaboration with Teltron, Inc., we sealed vacuum-tight CTP anodes onto focus-projected scan (FPS) vidicon camera tubes bodies in place of the customary photoconductive PbO targets. The FPS vidicon gun tubes provide many features that make it suitable for the e-MLM. Mechanically, they are compact, lightweight, and rugged. The linearity of the scan is excellent, and the beam diameter is small, ~20 μm. These vidicons are designed to operate at low electron-beam energies, which is an important consideration since the optimum beam energy for an efficient secondary electron emission from the CTP is a few hundred eV. Finally, the FPS vidicon can deliver a high current density on the order of 1 A/cm² to the target.

We produced a number of these sealed and gettered e-MLM tubes, which were then fitted with O-ring-sealed readout windows to provide a vacuum environment for the membrane. The readout windows had a clear aperture of 32 mm, and a 10° wedge to help compensate for the phase error induced by the off-normal incidence angle of the readout beam. The active diameter of the e-MLM was 20 mm. The device was tested as a black-and-white visible display by utilizing a spatially filtered Hg-Xe arc lamp as the light source.

Figure 16 shows photographs of images projected by the e-MLM onto a screen, using zeroth-order readout in a framed operating mode. The spatial resolution of these images is better than that in Fig. 13, primarily because of the smaller diameter of the addressing electron beam. The pixel geometries of the two devices are the same, 50-μm pixels on a 70-μm pitch. Because of, in part, the capacitive point spread of the CTP, the limiting resolution of this device is ≈3.5 line pairs/mm, or ~100 television lines.

V. Summary and Discussion of Results

We have demonstrated the operation of a MLM as a projection display with coherent visible, coherent midwave infrared, and white-light readout sources. Both 30-Hz video rates and flickerless operation have been achieved. Several forms of Fourier-plane spatial filtering were explored, but the preferred mode is the dark-ground technique, which consists of a central zeroth-order stop. This method yields a uniformly dark off state and a high optical readout efficiency, even for broadband light.

By using an improved means of fabricating custom-sized mirror pixel arrays, we optimized a modulator for the 3–5-μm wavelength band and achieved a contrast ratio of >100:1 with an optical readout efficiency of 75% by using the dark-ground readout technique. This means of fabrication yields uniform and highly periodic arrays of pixels, which minimizes high-frequency noise in the Fourier plane. The principal sources of off-state irradiance in the e-MLM are: (1) quiescent pullback of the membrane mirror into the wells, (2) aperiodicity of the pixel array, and (3) diffuse scattering from defects in the mirror surface.

The fact that the image information is impressed onto spatial carrier frequencies in the Fourier plane means that much of the diffuse scattering located between the orders can be blocked by constructing a spatial filter that passes the six first-order spots only, for example. We also note that the contribution of these background effects is dependent on the readout wavelength, so that an IR readout of a particular device should give a much darker off state, and, hence, a higher contrast ratio than when read out with visible light.

A two-dimensional calculational model that accurately predicts the intensities of the various orders as a function of membrane deflection was constructed. It also predicts the form of the projected image for the various forms of Fourier-plane spatial filtering, at least for the special case of an array of uniformly deflected pixels. Work is currently in progress to extend this model to include arbitrary two-dimensional images, and to study the optical effects of deflecting a few pixels only. The ability to model accurately device performance is useful in providing guidance to both device and system design. The dependence of the output irradiance on the pixel fill factor, which is illustrated by Figs. 7 and 8, is one example of the utility of the model.

Since CTP technology is scalable, we are planning to fabricate large-area CTPs to increase the number of phases.
of resolution elements. For example, increasing the device diameter to 2 in. (5.08 cm) and reducing the pixel pitch to 32 µm would yield 1024 × 1024 pixels in a square array format. If we consider two pixels in each dimension as constituting one resolution element, the device should support full 512 × 512 imagery. Although a finer pixel pitch places more constraints on the electron-beam diameter and on the device fabrication process, it also increases the optical throughput of the projector. This is due to the fact that the higher orders in the Fourier plane become more separated from the zeroth order as the pitch is reduced, relaxing the phase-space-limited constraints on light source extent and beam collimation. Once full video resolution is obtained, a full-color display may be constructed by using three SLM’s and a beam-combining system with the filtered output of a white-light source.

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References and Notes


20. The 406-HT flange-mounted all-electrostatic gun is available from Apex Electronics, Passaic, N.J.


22. The flange-mounted phosphor screen was supplied by Kimball Physics Inc., Wilton, N.H.


24. The Teltron Model 1301 vidicon was supplied by L. D. Miller, Teltron, Inc., Birdsboro, Pa., 19508.

