High-Resolution Laser-Projection Display System Using a Grating Electromechanical System (GEMS)

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ABSTRACT

Eastman Kodak Company has developed a diffractive-MEMS spatial-light modulator for use in printing and display applications, the grating electromechanical system (GEMS). This modulator contains a linear array of pixels capable of high-speed digital operation, high optical contrast, and good efficiency. The device operation is based on deflection of electromechanical ribbons suspended above a silicon substrate by a series of intermediate supports. When electrostatically actuated, the ribbons conform to the supporting substructure to produce a surface-relief phase grating over a wide active region. The device is designed to be binary, switching between a reflective mirror state having suspended ribbons and a diffractive grating state having ribbons in contact with substrate features. Switching times of less than 50 nanoseconds with sub-nanosecond jitter are made possible by reliable contact-mode operation. The GEMS device can be used as a high-speed digital-optical modulator for a laser-projection display system by collecting the diffracted orders and taking advantage of the low jitter. A color channel is created using a linear array of individually addressable GEMS pixels. A two-dimensional image is produced by sweeping the line image of the array, created by the projection optics, across the display screen. Gray levels in the image are formed using pulse-width modulation (PWM). A high-resolution projection display was developed using three 1080-pixel devices illuminated by red, green, and blue laser-color primaries. The result is an HDTV-format display capable of producing stunning still and motion images with very wide color gamut.

Keywords: MEMS, optical, grating, modulator, laser, projection, display

1. INTRODUCTION

Laser based projection display systems are of increasing interest with the appearance of new lower-cost solid-state laser technologies for generating red, green and blue primaries and spatial-light modulators well-suited for use with laser light. Combining these technologies in demonstration display systems has made clear the advantages for laser-projected images having significant color and image quality improvements. Also, in today's display markets, large numbers of individually addressable pixels, over one million, in area arrays are needed to meet the image resolution demands.

Electromechanical gratings have been developed for a variety of applications, including display, spectroscopy, and printing. The Scophony Home Receiver [1], demonstrated in 1939, was the first display system to make use of diffraction coupled with scanning methods to produce images. More recently, two distinctively different types of spatial light modulators containing arrays of electromechanical grating pixels were developed for display applications: viscoelastic membrane devices [2,3] and the grating light valves (GLV) of Silicon Light Machines [4,5]. Both of these modulator technologies use electrostatic actuation to produce surface deformations. Viscoelastic membrane devices utilize a metallized elastomer gel that is deformed to produce a sinusoidal grating profile, whereas GLVs have interdigitated suspended ribbons of metallized silicon nitride that are selectively deformed to produce a square grating profile.

This paper describes the operation of a conformal grating electromechanical system (GEMS) in a laser-projection display system. The GEMS device is a new design for a spatial light modulator based on diffractive optical MEMS technology

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that has been developed in the research and development laboratories of Eastman Kodak Company [6]. Electrostatic force is used to deflect a reflective membrane causing the appearance of a surface relief pattern in the form of a grating. Control of an applied voltage provides modulation of light beams diffracted from the grating. This development effort has produced: a fabrication process compatible with CMOS foundry facilities, device design optimization and performance methodology, device package and electronic architecture, prototype display systems, and image science methods for color and tone scale optimization.

2. DEVICE DESIGN AND FABRICATION

The structural design and operation of a GEMS device fabricated on a silicon substrate are shown in Fig. 1. The materials set and properties for the layers within the device can be generated from standard CMOS processing equipment; silicon dioxide, silicon nitride and aluminum. As shown in Fig. 1, the structural design consists of tensile electromechanical ribbons suspended over a number of identical parallel channels. These ribbons are bi-layer structures where the primary contribution of tensile stress is from the lower nitride layer, and the upper metal layer acts as a reflector and conductor. The support structure beneath the ribbons consists of a sequence of layers of oxide and nitride deposited on the silicon substrate and patterned to optimize the device performance. The design of these layers determine the electrical requirements for actuation, the efficiency of diffraction at the wavelengths of interest, and the robustness of the device by elimination of ribbon sticking. This alternating sequence of materials yields good adhesion between layers and each sub-layer serves as a highly-selective etch stop as the layers are patterned.

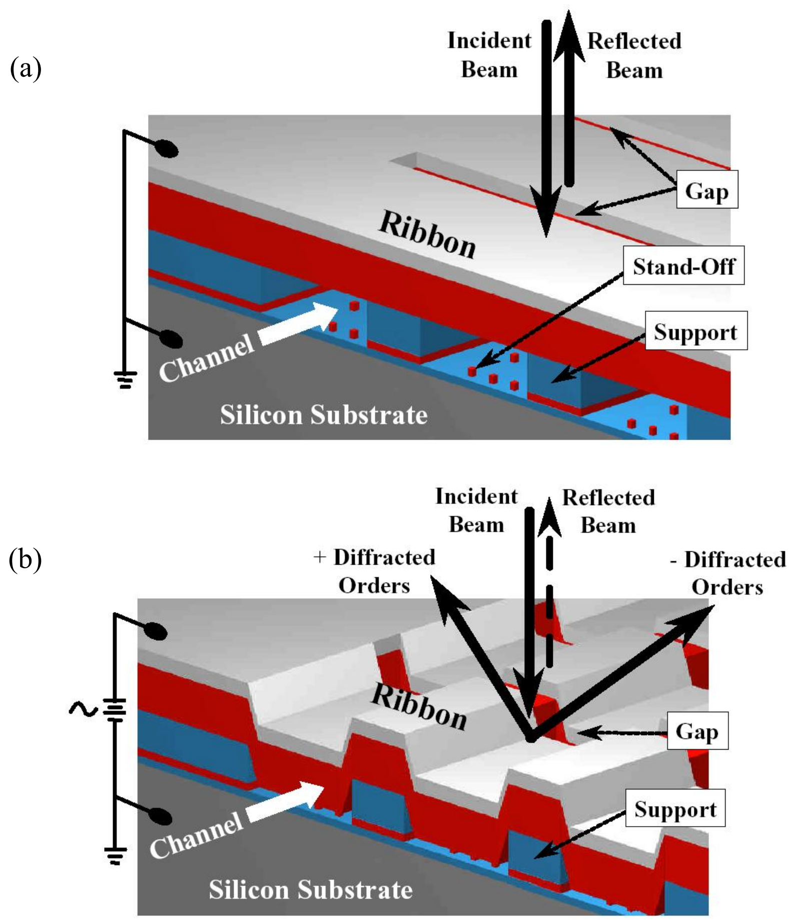
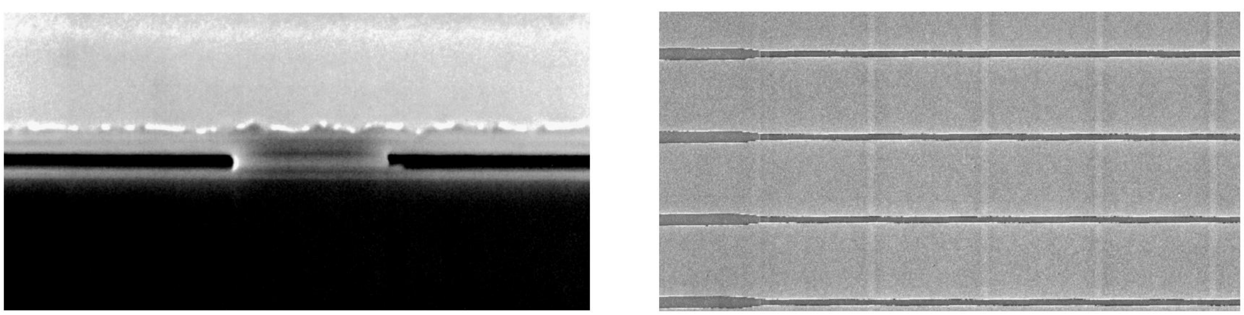


Fig. 1. An illustration of the GEMS device with the vertical scale greatly amplified relative to the horizontal, which shows a) the un-actuated state, where the ribbons are suspended flat, and b) the actuated state where the intermediate supports are revealed as the ribbons conform to the device substructure and the incident beam power is redistributed among several diffracted beams.

The first layer added to the silicon (see Fig. 1a) is a uniform oxide that acts primarily as an etch stop. The next layer is nitride patterned to produce standoffs. The standoffs minimize contact area when the ribbon is pulled down (see Fig. 1b). Next, a second oxide layer defines the key characteristics of the grating; 1) its thickness is the pull down distance of the ribbons and the resulting height of the surface grating, 2) the separation of the intermediate supports determine the grating period, 3) the channel width and support width affect the duty cycle of the grating and the efficiency and distribution of power in the diffracted orders and 4) the number of periods determine the active area of the device that can be illuminated. Before the addition of the final nitride and metal layers, the channels are filled with a sacrificial material. The filled channels are planarized with chemical mechanical polishing. The planarity of the resulting surface is critical to ensure good optical contrast for an operating device. The appearance of any intermediate support pattern at the surface in the unactuated-state of the device produces a "leaky" optical modulator having low optical contrast. Finally, the ribbon layers are added and patterned to produce gaps between ribbons and define the pixel dimension along the channel length. The gaps between the ribbons provide access to the channel for removal of the sacrificial material

The device features are defined by a step-and-repeat photolithographic mask process having a typical die-exposure area of 2 cm x 2 cm. Because of the relatively coarse device features, the length of the linear array can be extended across the entire wafer by stitching the stepper pattern. This approach allows the number of pixels within a device to be selected during packaging. In practice, the length of the array is constrained by the number of die-exposures, the process uniformity, and packaging considerations.

In the un-actuated state, with no voltage difference between the ribbon metal and the substrate, the ribbons are suspended flat in tension above the channels and the device functions as a plane mirror. The channels are separated by intermediate supports, which have a periodic spacing. The best designs, in terms of device operation and use in a practical optical system, typically have a period value between 25 μm and 50 μm. Ideally, the periodic substructure is completely hidden under the ribbons in the unactuated-state. A single pixel typically has more than one suspended ribbons, each attached to several intermediate supports. In practice, the effects of stress differences with the ribbon structure and the requirement for removal of the sacrificial material from the channels limit the ribbon width during device fabrication. There is no fundamental limit on the number of ribbons per pixel or the number of intermediate supports. Figs. 2a and 2b show cross-sectional SEM micrographs of a GEMS device to illustrate one design for the support and ribbon structure and the true aspect ratio of a device thin-film assembly. It should be pointed out that these results pertain to an early device design that was not optimized.



(a) (b)

Fig. 2. SEM micrographs showing a) a cross-sectional view that demonstrates the height aspect of a 1 μm wide support and b) a top-view of the GEMS device ribbons (10.6 μm horizontal structure) and the hidden supports (vertical substructure).

To actuate the device, a voltage is applied between the ribbon metal and the silicon substrate, creating electrostatic force to cause the ribbons to deform into the parallel channels to reveal the substructure hidden below, as depicted in Fig. 1b. When the device is fully actuated, the ribbons contact the standoffs on the substrate that reduce the potential area of contact, eliminating ribbon failure by stiction. The semi-conformal grating formed by this ribbon deformation has a trapezoidal-like profile that agrees well with our electromechanical models. The device design can be optimized for diffraction efficiency by adjusting the dimensions of structural features. In an RGB display system, the device design can be centered for maximum multi-order efficiency (up to 70%) in the green channel, while still providing excellent efficiency in the red and blue channels. Alternatively, the device in each color channel could be independently optimized. The modulation contrast for the diffracted orders is generally greater than 2000:1 for a device mounted in a package with an AR coated coverglass.

3. DEVICE OPERATION

Figure 3 shows the measured response of a fabricated GEMS device as a function of voltage applied to the ribbon. These results were obtained by illuminating the device with a 680 nm laser beam and measuring the light output in the 0^{th} and 1^{st} orders, while driving the device with a bipolar 10 KHz triangle wave. At this relatively low frequency, the device response is essentially instantaneous and is the same as the static response to a DC voltage. Bipolar actuation waveforms prevent charge accumulation in the dielectric layers. The plot in Fig. 3 shows only the response to positive voltages. The negative voltage response is identical, because the electrostatic force affecting the ribbons is proportional to the square of the applied voltage. Below the release voltage, 13 V, the ribbons are suspended (partially actuated) above the substrate and only a small percentage of the incident light is diffracted out of the 0^{th} order. Above the pull-down voltage, 20 V, the ribbons are fully actuated and nearly all of the incident light is diffracted out of the 0^{th} order into the non-zero diffracted orders. Between these two critical voltages, the response is bi-stable and depends on the most recent state.

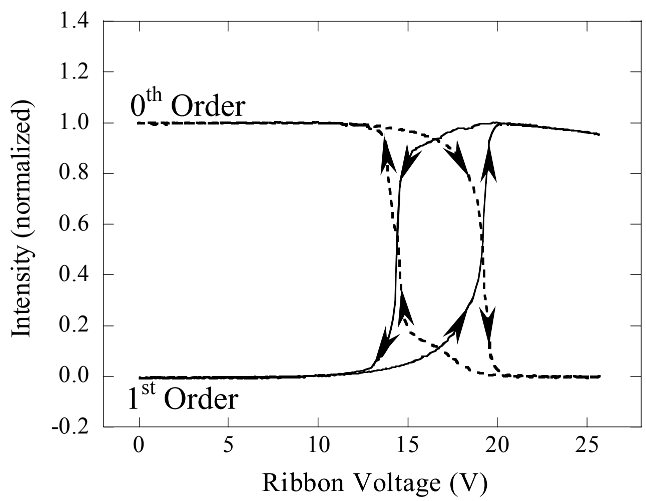


Fig. 3. Measured light intensity in the 0^{th} and 1^{st} order beams as a function of applied voltage showing hysteresis. The arrows in the bistable region indicate the permitted direction of travel. For this particular device, ribbon length is 35 µm and the height of the ribbon above the standoffs is 180 nm.

The device is intended to be used digitally by switching the applied voltage between 0 V and a drive voltage above pull-down that produces stable device operation. Figure 4 shows the dynamic response of the device of Fig. 3 to a digital pulse-width modulated (PWM) data stream. The applied voltage is a random bipolar waveform with 10 different pulse-lengths separated by 25 ns intervals. The optical rise-times are ~50 ns during turn-on and ~30 ns during turn-off with optical edge jitter less than 0.5 ns (see Fig. 4b). The optical-edge jitter is the result of both the electronic driver and device jitter and represents the level of control that can be achieved in the output intensity. Noise and operational frequencies associated with the light source also contribute to the jitter, so the measurements of Fig. 4 are representative of an overall system jitter for our specific test system. The particular driver rise-times and device geometry in this experiment were chosen to keep the ringing in the optical response relatively small.

The response to the random PWM data stream demonstrates how the device is used in an imaging application. The relative brightness, or gray level, for an individual pixel is proportional to the integrated intensity during a pixel's display period. The ability to define gray levels in an image is therefore, limited by the system jitter.

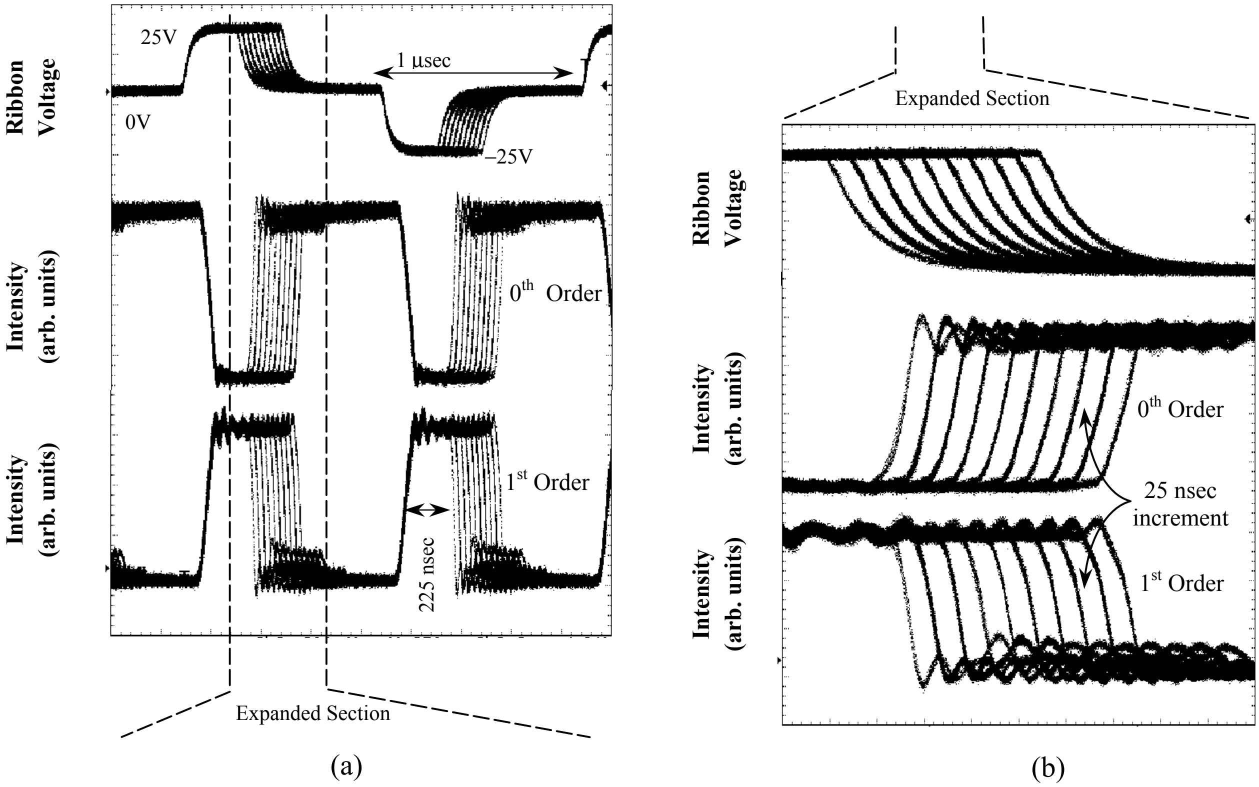


Fig. 4. Oscilloscope traces of the high-speed response of a conformal GEMS device to a random PWM data stream, showing the 0th and 1st order light intensities: a) complete ribbon voltage waveform and b) expanded section.

4. IMAGE GENERATION

A color-channel is created using a linear array of individually addressable GEMS pixels illuminated by a laser light source. Figure 5 illustrates a laser beam that has been shaped to produce line-illumination within the active area of the GEMS device. The static-beam width at an image plane is defined by the intensity profile of this line (i.e., perpendicular to the linear array of pixels) and is primarily determined by the initial laser beam quality and optics for shaping and delivering the beam to the active area of the GEMS device. As a general rule, to obtain good contrast and easy selection of diffracted orders, at least 1.5 periods are illuminated with the full-width half maximum (FWHM) of the intensity profile. The height of a pixel is simply determined by the number of ribbons connected together to form a pixel and the associated ribbon dimensions. In our initial system, designed for 2-inch diameter optical elements, the GEMS device was a 40 mm chip with a 0.36 mm wide active area, a grating period of 36 µm, a pixel height of 36 µm with 4 ribbons per pixel, and 1080 total active pixels. Additional dummy pixels were included at the ends of the active device to avoid edge effects appearing in the image plane.

An alternative design with an 18-µm pixel height, allowing 1080 pixels on a 2 cm chip, was also fabricated. This design can be used with smaller lower-cost optics or can be packaged in longer lengths, enabling an even higher pixel count. The FWHM requirement on the illumination beam results in asymmetric pixels at the image plane for the 18-µm pixel device. The pixel aspect ratio can be adjusted, however, with anamorphic projection optics.

In the linear array direction, beam intensity variations and roll-off can be corrected to achieve the uniformity required for good quality image generation. Molded optical elements have been designed and fabricated to properly shape the beam in this dimension and, assuming an ideal Gaussian beam supplied to this lens, a theoretical 90% collection efficiency onto the active area of the GEMS device is possible. Experimentally we have achieved 80% with our first lens attempts. The effects of residual non-uniformities are calibrated out of the displayed image.

In our optical system, when the device is in the unactuated state (OFF), the active area behaves as a mirror and incident light is reflected and blocked by an optical stop. Figure 5a illustrates the incident and reflected beam cross-sections in the vicinity of the active area of the GEMS device. When the device is turned on, the diffracted optical beams appear with sufficient diffraction angles to pass around the optical stop. Figure 5b illustrates the diffracted-beam cross-sections for with two of the pixels in the actuated state (ON). Only representative positive and negative diffracted orders are shown here. Within the projection display system, the $\pm 1^{st}$, $\pm 2^{nd}$, and $\pm 3^{rd}$ symmetrical diffracted orders are created by the GEMS device and are all easily isolated from the zero-order beam and collected through the optical elements. These diffracted beams are imaged using projection optics onto the screen surface where they converge to form a line image.

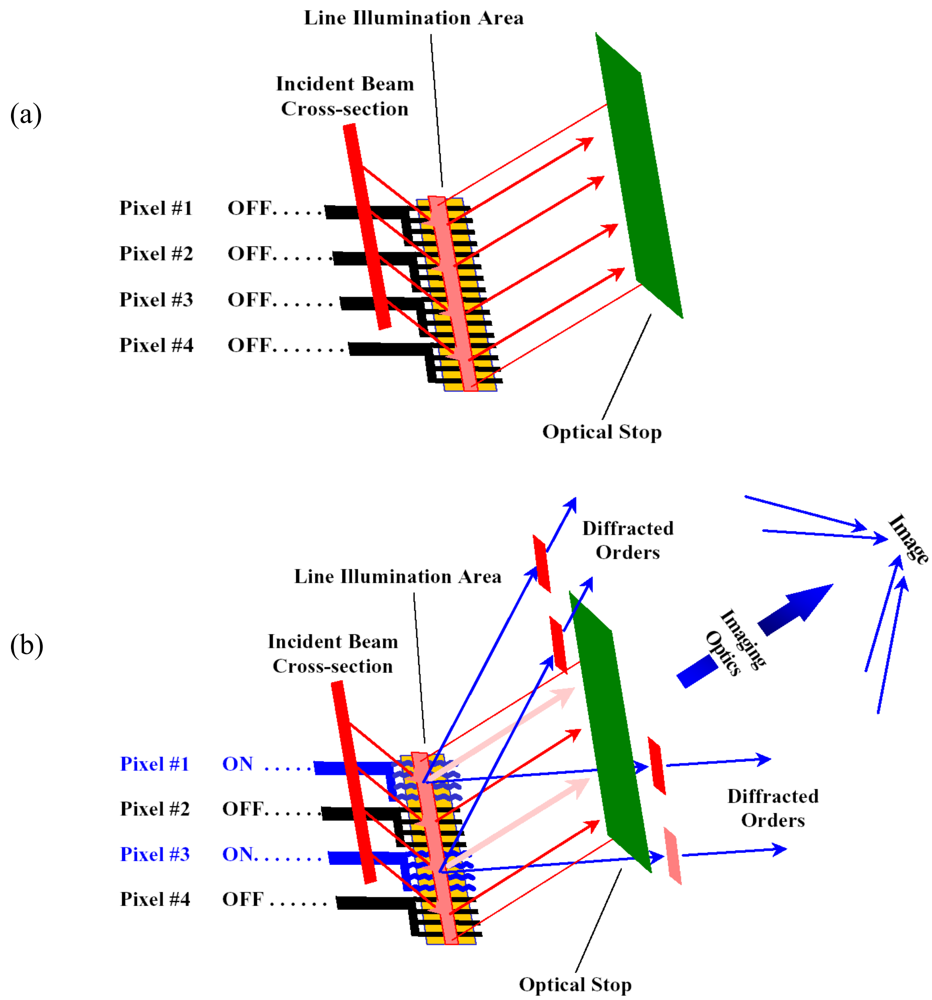


Fig. 5. Illustration of the GEMS array operation showing a) a linear array of pixels in the unactuated state (OFF) with the reflected optical beam blocked by an optical stop and b) pixels in the actuated state (ON) that create diffracted beams that pass around the optical stop and through imaging optics.

A two-dimensional image is formed by scanning the line image using a rotating mirror and sending each pixel a voltage waveform that is synchronized with the mirror scan, as illustrated in Fig. 6. A linear asymmetric scan is used rather than a symmetric scan since it produces flicker-free images at lower scan frequencies (60 Hz). The device is supplied with center-weighted PWM data derived from a SMPTE-292 data source (1080i format, 30 Hz interlaced frames). A GEMS-linear array with 1080 pixels is imaged vertically onto a viewing screen and scanned horizontally at a 60 Hz frame rate. The data display time is currently about 80% of the scan, 13.4 ms, and within this period, 1920 vertical lines are displayed, each having a line time of 7 µs. For each color-channel at 11 bits of pulse width modulation, the LSB time is 3.4 ns. This is significantly more than the system jitter, ensuring good control of the gray-scale. In principal, for this margin of control and horizontal resolution, it is possible to display a gray scale with 13 bits per pixel of digital control of the light modulation. In addition, because the raw data feed to the device occurs at a 60 Hz frame rate, the system is capable of displaying images from a 1080p data stream, where each frame contains completely new content. The shape of each pixel on the screen is fixed in size in the vertical direction and is dynamic in the horizontal direction. This dynamic beam width at the image plane is the convolution of the intensity profile of the static-pixel width with its PWM "on time" window. Since the PWM "on time" determines the gray level, the horizontal pixel shape is gray-level dependent. This variable pixel shape produces fewer image artifacts than spatial light modulators having a fixed pixel shape.

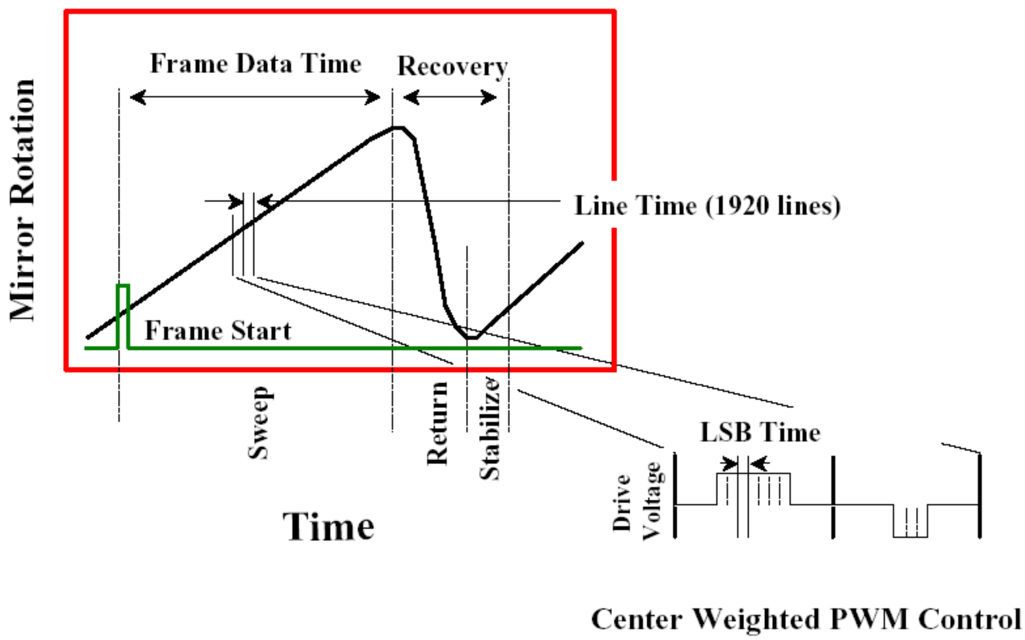


Fig. 6. Illustration of center-weighted pulse-width modulation used with the GEMS device, where a scanning-mirror galvanometer is used to create a two-dimensional projected image.

The GEMS device is well suited for use with a digital data stream, because of its high-speed response. However, for low-bit intensity values, there is a nonlinear behavior of the device associated with the pull-down and release of the ribbons during approximately the first 100 ns of these transitions (see Fig. 4). This is due to the mechanical delay and resonance properties of the ribbons. Modulating the device using fast rise-time driver electronics produces a rapid device response but also introduces the resonance into the grayscale, producing a nonmonotonic behavior in the dark levels. This non-monotonic grayscale is illustrated in Fig. 7, where the integrated relative intensity, or gray level, is plotted as a function of driver pulse width. A family of curves is presented for different driver rise-times to illustrate the problem and the monotonic response achievable with slower driver rise times. In addition to providing a monotonic response, slower driver rise times produce a non-linearity for low pulse widths that provides an even higher effective bit depth for dark levels. This method therefore allows for improved control of the gray scale and takes advantage of the very low jitter associated with the device.

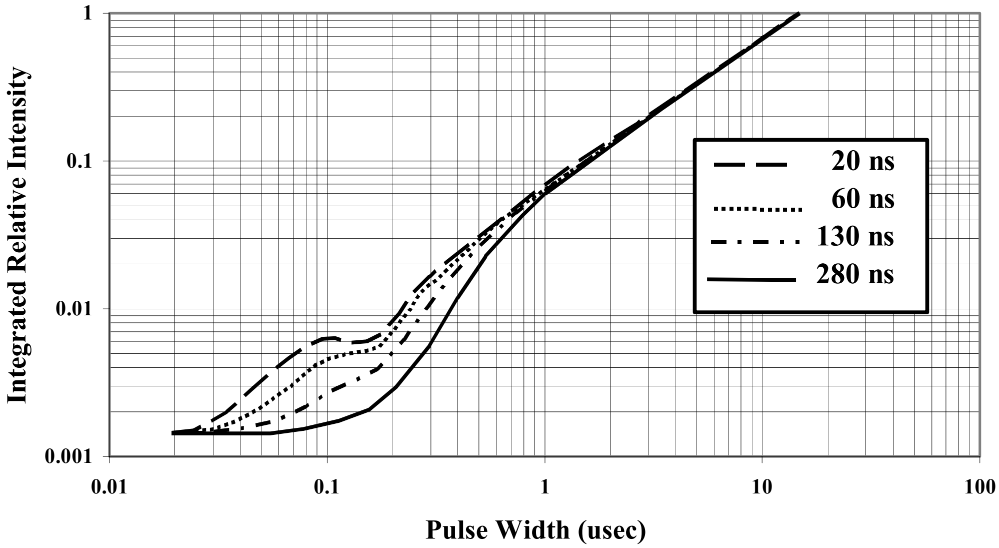


Fig. 7. A plot of the relative integrated intensity vs the electronic driver pulse width for a family of driver rise times (10% to 90%).

5. PROJECTION DISPLAY RESULTS

A color-display system is created by combining red, green, and blue optical channels using conventional optical elements as illustrated in Fig. 8. The laser beam is conditioned to efficiently illuminate the GEMS device as described above. Optical beam conditioning is an important aspect of this design to maximize the efficiency of laser light usefully delivered to the GEMS devices. As illustrated in Fig. 8, the linear array length extends out of the page. The micro-mirror serves two purposes, introducing the laser beam into the system and stopping the reflected zero order from continuing into the projection optics. Because the grating period of the GEMS device is oriented perpendicular to the length of the array, the diffracted orders can be separated from the zero order prior to the projection optics. The diffracted orders for each color are combined using an X-cube designed for the particular wavelengths. Finally, an achromatic projection lens and scanning-mirror galvanometer are used to image the device onto the viewing surface (front or rear projection) and create the two-dimensional image with scanning. The primary optical system efficiency issues include: 1) delivery of light to the device, 2) device diffraction efficiency, and 3) need for recovery time by the scanning solution. A practical value for the maximum system efficiency is 40%. Table 1 presents the system specification for demonstrated GEMS-based display system. The system is similar to Fig. 8, except the order of the projection optics and X-cube is interchanged.

A significant need in high-end display systems (e.g., entertainment, training simulators, command and control, etc.) is immersive-type display where the image aspect ratio is much higher than the 16:9 value found in HDTV. The horizontal axis is extended significantly, requiring many more pixels. Usually this is achieved by using multiple-display systems stitched together to form the final image, often producing unpleasing seams. With the combination of the very high resolvable bit depth and the scanned linear image, the GEMS device is well suited for increased resolution in the horizontal scan direction. Using a flexible prototype system, we have demonstrated the capability of creating a seamless image that has 7680 x 1080 pixels with 9 bits per color-channel. Because the device length can be extended, as described above, the number of pixels within the linear array, corresponding to the vertical direction on the screen, is primarily dependent on the limitations of device packaging and data delivery rates. With proper system design, much higher resolution can be obtained in the vertical axis with higher bit-depth per color-channel.

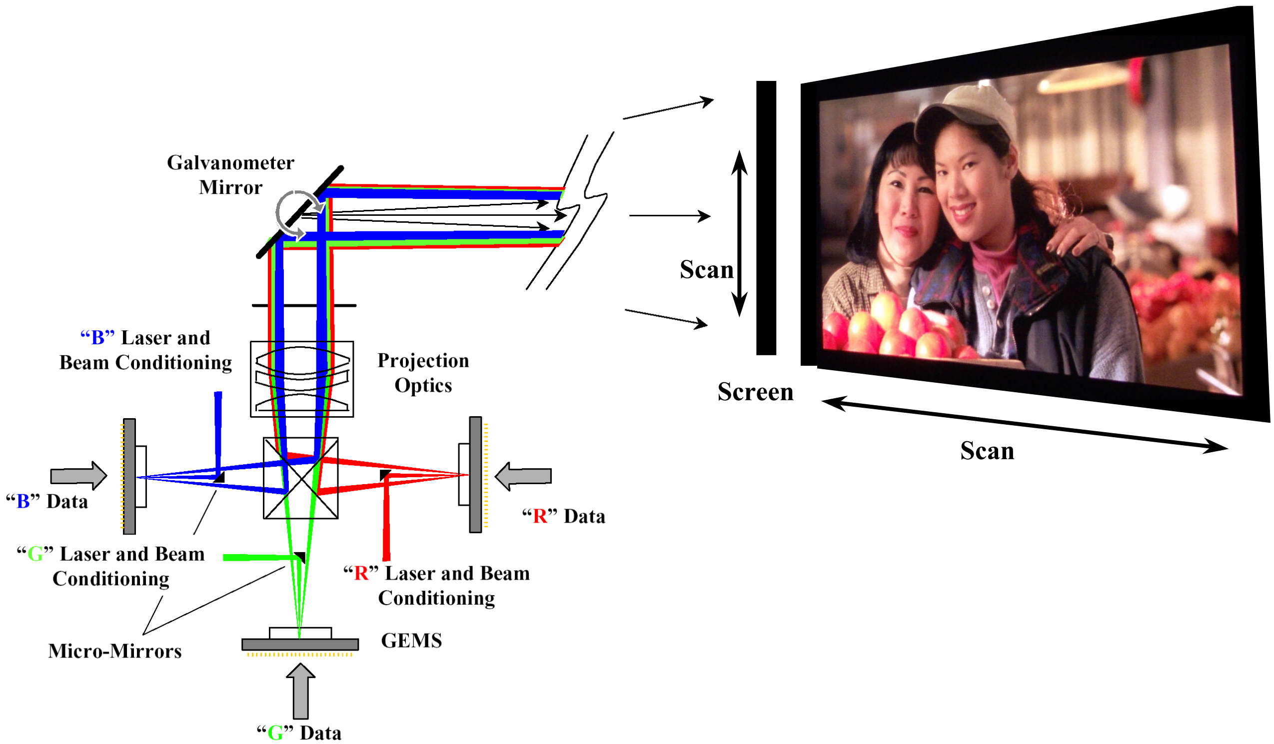


Fig. 8. The basic optical system is illustrated to show illumination of the GEMS device, beam combination, projection optics and 2D image generation by scanning.

Table 1. Specifications for laser projection system.

Laser Power (total RGB)	10 W
Vertical Resolution (device pixels)	1080
Horizontal Resolution (scan lines)	1920
Frame Rate	60 Hz
Display Bit Depth (per color)	11 bit
System Contrast (ANSI checkerboard)	>250:1
System Contrast (frame-sequential)	>1000:1
Data Stream	1080i
Size	115 in. diag

A major advantage for laser projection systems is the use of lasers at selected wavelengths that expand the color gamut available to display. Using three monochromatic colors, the area of the color gamut is significantly increased compared to conventional lamp-based displays. The gamut enables the creation of more life-like images through image science and ability to produce extremely saturated colors in computer-generated imagery for simulation or gaming. Figure 9 shows a comparison of the 709 standard display, high-end lamp-based projection systems and the GEMS laser-projection display at Kodak. The laser primaries are 440 nm, 532 nm, and 630 nm. The result is an HDTV-format display capable of producing stunning still and motion images.

A concern for use of lasers in projection systems is image noise from speckle associated with the coherence of the projected radiation. Methods have been tested to reduce the speckle to a tolerable level, i.e., lowering the perceived speckle contrast. These methods include: 1) increasing the spectral incoherence by introducing laser line-width broadening, 2) creating spatial incoherence by moving a diffuser at an intermediate image plane, 3) dynamic motion of the screen, 4) screen characteristics that introduce volume scattering, and 5) depolarization methods.

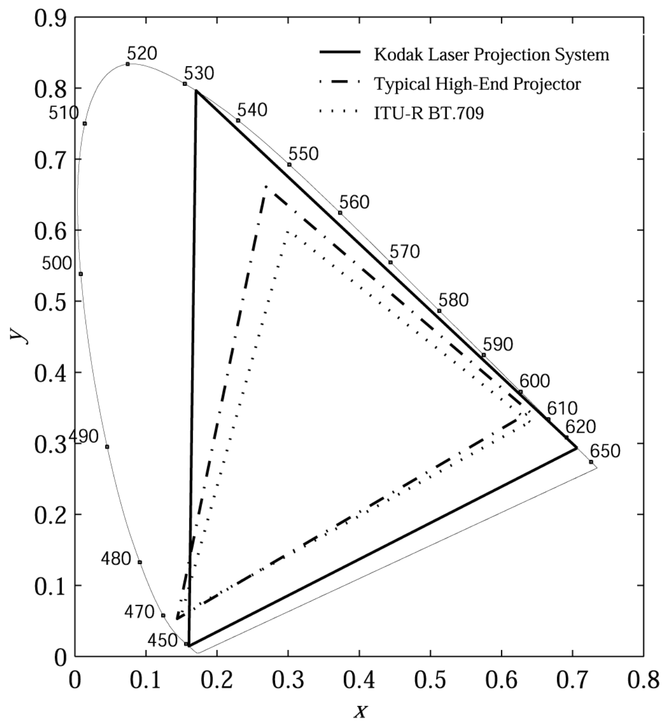


Fig. 9. Comparison of the color gamut space for display systems between: laser projection system (solid line), typical high-end lamp-based projectors (dot-dash line), and ITU-R.709 (dotted line).

6. CONCLUSION

We have developed a unique spatial light modulator, the GEMS device, which contains a linear array of optical MEMS gratings that provide high-speed digital light modulation. The optical performance, speed, and potential low cost of the device make it attractive for digital light modulation systems such as printers and displays. The device is designed to have a wide active region with a diffraction direction that enables the use of relatively simple and small optical systems.

In comparison to lamp systems with spatial light modulators, there are several advantages; 1) The perceived image quality is higher because of reduced pixelation and variable pixel shape (less prone to aliasing), with high contrast measured both frame-sequential and within-frame (ANSI). 2) The color gamut area is significantly expanded and colors are more appealing using laser primaries at properly selected wavelengths coupled with these image-science methods. 3) The higher bit depth available exceeds the requirements of content available today. 4) The horizontal resolution is extensible by increasing the scan angle and the number of display pixels, thus avoiding the need for stitched display systems that have discontinuities at the stitch boundaries. 5) The GEMS device is potentially much lower in cost as a spatial-light modulator in comparison to two-dimensional arrays, because of the reduced active area and associated increase in yield.

The GEMS device coupled with RGB laser radiation is capable of producing spectacular still and motion images that create a new visual experience. Images are life-like having a smooth continuous quality with no "screen door" effect, high contrast, extended dynamic range, high resolution, and vivid colors. In addition, computer-generated motion images can provide a unique experience by using the expanded available color gamut to produce highly saturated colors.

7. ACKNOWLEDGMENTS

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REFERENCES

[1] *Scophony Projection Television Manual* (http://www.tvhistory.tv/1938-Scophony-UK.htm). See also D. M. Robinson, "The Supersonic Light Control and Its Application to Television with Special Reference to the Scophony Television Receiver," Proc. I.R.E, 483-486 (1939).

[2] N. K. Sheridon, "The Ruticon Family of Erasable Image Recording Devices," IEEE Trans. Electron Devices, **ED-19**, 1003-1010 (1972).

[3] W. Brinker, W. Wirges, G. Przyrembel, R. Gerhard-Multhaupt, J. Klemberg-Sapieha, L. Martinu, D. Poitras, and M. R. Wertheimer, "Metallized Viscoelastic Control Layers for Light-Valve Projection Displays," Displays **16**, 13-20 (1995).

[4] O. Solgaard, F. S. A. Sandejas, and D. M. Bloom, "Deformable Grating Optical Modulator," Opt. Lett. **17**, 688-690 (1992).

[5] D. T. Amm and R. W. Corrigan, "Optical Performace of the Grating Light Valve Technology," SPIE Proc. **3634**, 71-77 (1999).

[6] M. W. Kowarz, J. C. Brazas, and J. G. Phalen, "Conformal Grating Electromechanical system (GEMS) for High-Speed Digital Light Modulation", IEEE, 15^{th} Int. MEMS Conf. Digest, 568-573 (2002).