67.2: Line-Scanned Laser Display Architectures Based on GEMS Technology: From Three-Lens Three-Chip Systems to Low-Cost Optically Efficient Trilinear Systems

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Abstract

The device structure of our grating electromechanical system (GEMS) linear array modulator enables unique optical architectures for line-scanned laser displays. We describe the optical system of our three-chip, front-projection GEMS prototype and a design for a high-performance, trilinear system that combines the simplicity of a single-chip system with the optical efficiency and image quality of a three-chip system.

1. Introduction

High-speed linear-array light valves [1-6] have attracted growing interest because of their ability to produce very high resolution displays, while requiring a substantially smaller active area than a comparable area-array light valve. In fact, recent demonstrations of line-scanned laser projectors have shown that the line-scanned approach is capable of producing spectacular image quality [3,5].

Eastman Kodak Company has developed a light valve for laser projection display known as the grating electromechanical system (GEMS) light modulator [2,5]. The GEMS modulator is a microelectromechanical device fabricated on silicon containing a linear array of electrically activated diffractive elements that switch between a reflective Off state (Figs. 1a and 1b), and a diffractive On state (Figs. 1c and 1d). The device works on the principal of a hidden grating, employing a periodic series of intermediate supports covered by ribbons to form a flat mirror surface. Electrostatic force causes the ribbons to conform around the supports, producing a grating structure in the On state that diffracts light into a number of orders. The GEMS array is laser illuminated and imaged by a simple optical system to form a column of pixels on the projection screen using several of the high-contrast diffracted orders. Sweeping the column of pixels across the screen creates a two-dimensional image. The GEMS modulator is digital in nature, switching between the reflective and diffractive states, which enables gray level generation through pulse-width modulation of the diffractive state.

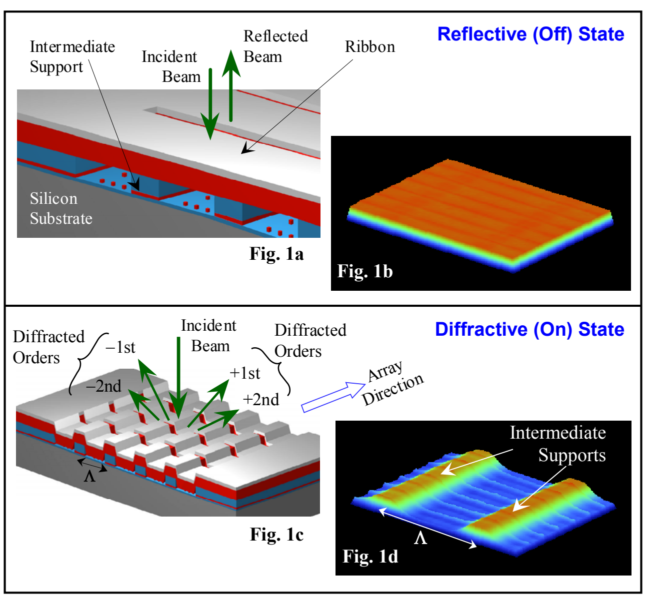

Figure 1 – Illustration of the GEMS pixel structure (Figs. 1a and 1c), with interferometric profilometry of the ribbon surface for a fabricated device (Figs. 1b and 1d).

Figure 2 – Photographs from a 115" front-projection GEMS laser display prototype showing (a) scanned motion picture film and (b) computer-generated imagery.

The resultant GEMS-based laser display system delivers high resolution, high native bit depth, and wide color gamut. The system is capable of displaying superb image quality for both camera-captured content (Fig. 2a) and computer-generated imagery (Fig. 2b). The technology provides a scalable device architecture, large active device area, compact optics, and simple optical design, making it a great choice for a wide range of projection display applications.

In this paper, we describe the unique optical configurations of laser display systems that are enabled by the GEMS device,

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starting with our three-chip, front-projection demonstration system and progressing to a high-performance trilinear array system that combines the simplicity of a single-chip system with the optical efficiency and image quality of a three-chip system. These simple optical system architectures are made possible because of the fundamental structure of the GEMS device, which features a linear array of diffractive pixels having a large active area with a grating period Λ oriented perpendicular to the array direction.

2. Three-Chip Three-Lens System

2.1 Optical System

The optical system configuration used in our three-chip, front-projection prototype is shown in Fig. 3. The primary goal of this system was to demonstrate the spectacular image quality that is possible in a GEMS display system. We therefore chose a three-lens system with post-lens RGB combination using an X-cube for maximum flexibility in experimentation. The array direction of the three GEMS devices is out of the page in Fig. 3. A key feature of GEMS-based systems, enabled by the orientation of the grating period and exploited in designing our demonstration system, is the ability to illuminate the device directly on axis and to separate reflected 0^{th} order light from diffracted orders in the vicinity of the device without using a lens to perform a Fourier transform. The demonstration system uses three ISCO Ultra-MC 150 mm cinema projection lenses, with an off-the-shelf X-cube and galvanometer, to produce a 1920(H) × 1080(V) pixel image having a 115-in. diagonal in approximately a 5.5-m throw. The system has a native bit depth of 11 bits per color and a frame-sequential contrast of 1500:1.

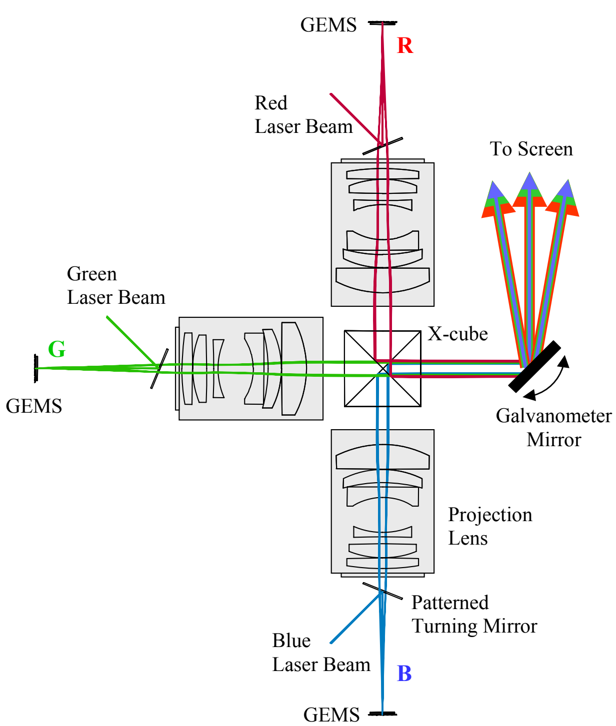

Figure 3 – Three-chip front-projection laser display prototype.

2.2 GEMS Linear Arrays

The GEMS linear arrays (see Fig. 4) have 1080 addressable diffractive elements, each with a 36 μm × 0.36 mm active area containing four ribbons and ten 36-μm periods, for a total array active area that is 38.88 mm high × 0.36 mm wide. The three arrays for the RGB display are of the same design; the device diffraction efficiency being centered for the green channel and allowed to roll off slightly for the red and blue channels. The devices have a suspended ribbon length of 30 μm, a ribbon width of 8.2 μm, and an actuation depth h of approximately 170 nm.

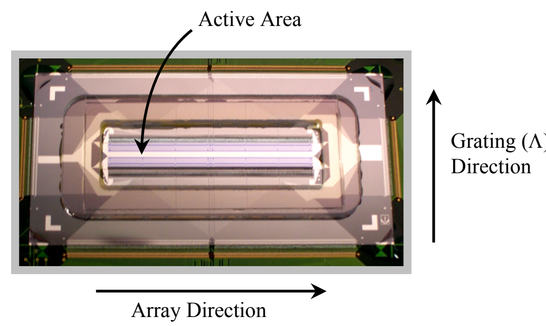

Figure 4 – Photograph of a 1080-pixel GEMS device.

RGB laser beams from a solid-state laser are conditioned to provide line illumination onto the arrays. Realizing the importance of a wide active area for defect tolerance, alignment tolerance, and accommodation of imperfect line illumination, the active area has been extended to over 1 mm wide in more recent versions of these arrays. Only a small portion of the 1-mm width is illuminated, typically less than 10%. If a device contains a point defect in the active area or on the cover glass, this built-in redundancy provides a nearby defect-free area that can be illuminated, significantly increasing device yield.

2.3 Illumination and Order Separation

As illustrated in Figs. 5a and 5b, a patterned mirror stripe on an antireflection-coated optical window provides an on-axis path for the illumination beams and also serves to separate the reflected 0^{th} order light from the diffracted orders. Reflected light is dumped out of the system. Diffracted orders pass through the optical window and are reimaged onto the screen. The demonstration optical system (Fig. 3) collects six orders (±1, ±2, and ±3) in the red and green channels and eight orders (±1, ±2, ±3, and ±4) in the blue for increased optical efficiency. Multiorder collection is possible in a GEMS-based system because all of the diffracted orders are high contrast and can be collected without significantly increasing the size or complexity of the optics.

To effectively separate the nonzero diffracted orders from the 0^{th} order, they need to be well angularly separated. Hence, in the diffraction plane, the angular content θ_l of the line illumination at wavelength λ incident on the GEMS device needs to be limited to approximately

$$\sin(\theta_l) < \lambda/\Lambda \,. \qquad (1)$$

Because the full-width half-maximum (FWHM) for a Gaussian laser line can be approximated by the relation

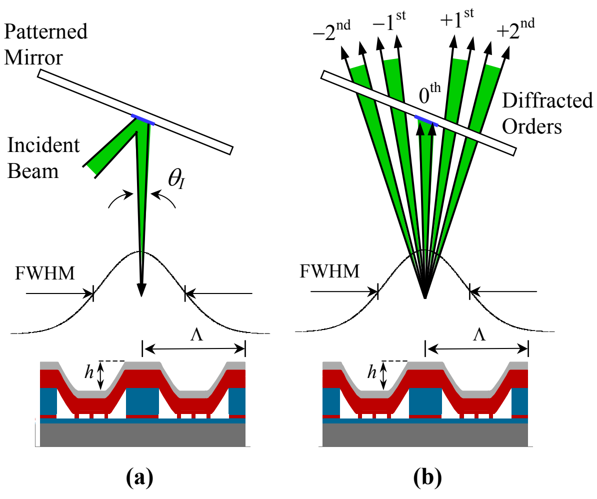

Figure 5 – (a) Illumination and (b) diffracted order separation using a patterned mirror.

$$\mathrm{FWHM} \approx \frac{0.55\,\lambda}{\text{numerical aperture}} \approx \frac{0.55\,\lambda}{\sin(\theta_I/2)}\,, \qquad (2)$$

the condition for order separation becomes

$$\mathrm{FWHM} > 1.1\,\Lambda\,. \qquad (3)$$

A good choice is FWHM ≈ 1.5 Λ, in practice, or 54 μm for our prototype devices. It should be pointed out that the reimaged line on the screen is actually sharper than implied by this criterion because of interference that occurs between multiple orders in the image plane.

2.4 Light Beam Paths

The path of light beams through a GEMS-based system is unlike that of any other line-scanned display system. As an example, Fig. 6 illustrates the propagation of the diffracted orders in various parallel planes for the green channel of our demonstration system. The perpendicular orientation of the grating period relative to the array direction causes the various diffracted light beams to separate from each other after propagating just a short distance, typically within a centimeter or so from the GEMS array, and allows relatively small optical elements to be used. Furthermore, the diffracted beams remain separated throughout the optical system until an image plane is reached, allowing the individual orders to be manipulated almost anywhere in the system. To minimize the size of the scanning galvanometer mirror, it is placed near the Fourier transform plane of the projection lens (see Fig. 6f). The diffracted orders recombine close to the screen into a single line.

3. Trilinear Array System

3.1 Advantages and Challenges

For lower cost and more compact systems, a traditional color-sequential approach could be employed where the RGB laser illumination beams are cycled onto a single GEMS array. This method, however, requires approximately three times the peak light output from each of the lasers, causes color breakup, and reduces the image bit depth and/or resolution. It is therefore highly desirable to develop a trilinear system that combines the optical efficiency and image quality of a three-chip system with the simplicity and cost-effectiveness of a single-chip system.

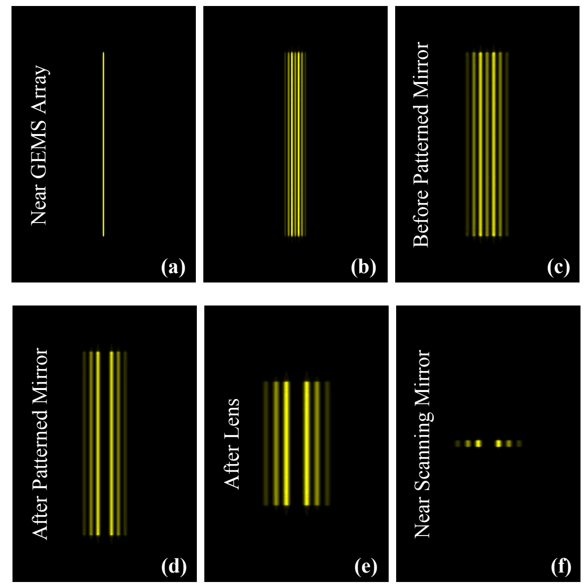

Figure 6 – Propagation model for diffracted light beams in a GEMS system.

Although multilinear CCD arrays have been successfully employed in line-scanned cameras and scanners for many years, the adaptation of the concept to a laser display faces additional hurdles because of the need to provide both an illumination path to and a projection path from the multiple linear arrays. Several options can be considered for illuminating a trilinear array light valve, including: (a) off-axis illumination onto a tilted device, (b) on-axis illumination through a patterned mirror located at a Fourier transform plane of the projection lens system, (c) on-axis illumination through an optical isolator (waveplate and polarization beamsplitter), and (d) on-axis illumination through a patterned mirror located before the projection lens system. The first three approaches require significant compromises to implement: option (a) results in difficulties with focus and magnification for the three linear arrays, option (b) results in contrast-reducing lens reflections and causes implementation challenges because the Fourier transform plane is also the best location for the scanning mirror, and option (c) requires a large aperture and expensive multiwavelength optical isolator and places additional polarization constraints on the incident laser beams. Option (d) is the simplest and most cost-effective to implement. Fortunately, this option is readily supported by the GEMS device design because of the orientation of the grating period Λ and the spatial separation of the diffracted orders. Other linear light valves, such as the grating light valve [1,3,6] and the flexible micromirror array [4] are not well suited for this approach.

3.2 Initial Design

Figure 7 shows our initial design for a trilinear GEMS system using an optical window with a single mirror stripe in the illumination path. This design is based upon a trilinear device that has three 1080-pixel linear arrays with 18 μm pixels, an 18-μm period Λ and a center-to-center separation of 500 μm between the arrays. The mirror stripe blocks the reflected 0^{th} order light from all three of the linear arrays. An alternative approach that provides more separation between the linear arrays for

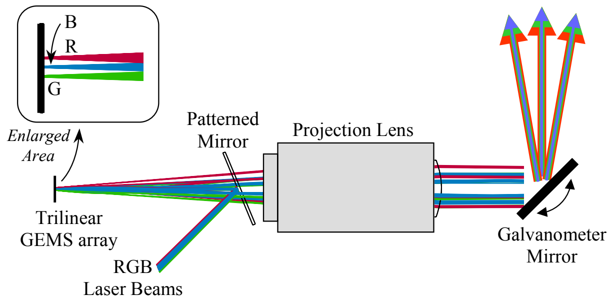

Figure 7 – Trilinear GEMS array system.

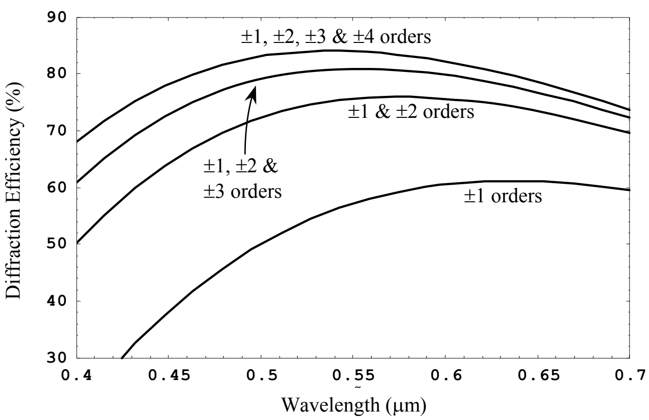

Figure 8 – Calculated multi-order diffraction efficiency.

interconnects uses three mirror stripes, one for each of the arrays. Gaps between the mirror stripes then allow the diffracted orders to pass through the system.

Using the same design for the three GEMS arrays and an optical system that collects multiple diffracted orders, the calculated diffraction efficiency based on our verified optoelectromechanical model is above 70% for RGB wavelengths (see Fig. 8). Here the device model assumes aluminum-covered ribbons with a 94% fill factor. As shown in Table 1, depending on the optimization of other components, the trilinear system is expected to have an optical throughput of greater than 36%. A trilinear GEMS laser display architecture will therefore be able to make much more effective use of available peak laser power than a conventional, low-cost projection system design that is color sequential.

4. Conclusion

GEMS technology enables laser display architectures that simultaneously provide superb image quality, high optical efficiency, and simple designs that have the potential for low cost. The ultimate commercial success is dependent on the emergence of low-cost RGB display lasers. Progress on that front is very promising, as evident by the work on display lasers being presented at this conference [7-10].

Table 1 – Expected efficiency of a trilinear system.

	Expected	Optimized
Line Generation Optics	0.88	0.95
Illumination Overfill	0.92	0.95
Uniformity Calibration	0.92	0.95
GEMS Device Efficiency	0.68	0.75
GEMS Device Duty Cycle	0.95	1.00
Galvanometer Duty Cycle	0.85	0.90
Galvanometer Mirror	0.98	0.98
Projection Lens	0.95	0.95
Dichroic Combiner	0.95	0.98
Trilinear System Total	**0.36**	**0.53**

5. Acknowledgements

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6. References

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