GEMS: A Simple Light Modulator for High-Performance Laser Projection Display

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ABSTRACT

GEMS (grating electro-mechanical system), a digital MEMS-based linear light modulator array, will be described. Implementation of the GEMS device in a 1080p laser front-projection display demonstration system will be discussed. The very high native bit depth and resolution, extremely fast line time (no motion blur), together with the use of spectral primaries and absence of visible pixel boundaries, result in a display with superb image quality, even for still images. Preferred methods for calibration and color transformation will be disclosed.

INTRODUCTION

The rapid progress in the development of low-cost red, green, and blue (RGB) lasers [1] in the one-Watt per color regime and higher is intensifying interest in laser television (TV). Of course, the future of rear-projection display remains uncertain in the face of continuing price drops in flat panel displays. Nonetheless, micro-display projection TV provides the highest image quality per unit price for larger picture diagonals. The long life of lasers together with the potential for higher screen flux (allowing lower screen gain with improved viewing angle range) stand to address two of the remaining issues with projection TV. The extremely low etendue of laser sources also allows the use of smaller modulators and, therefore, the potential for still lower cost. These benefits, together with the ultra-wide color gamut provided by lasers, could extend the value position of micro-display projection TV.

After lasers, the next key components include the means for light modulation/scanning. Architecture choices include 2-axis raster scanning with modulation of the input laser beams (either direct or via external modulators), linear modulator with single-axis scan, or two-dimensional (2D) spatial light modulation. Of these, the last is likely to become the first example of commercially introduced laser HDTV, using the Texas Instruments Digital Micro-mirror Device (DMD) modulator. Excellent results have been achieved in a prototype laser TV presented at SID in 2006. Although the 2-axis scanner architecture with direct diode modulation is attractive for its simplicity and its potential for a compact design, it is generally agreed that it will be a great challenge to achieve the full HDTV format (1080i or 1080p) and/or larger screen sizes using the approach. This is due to limitations in the scanner (spot-size bandwidth product), in the laser modulation speed, and in the power scalability of the corresponding lasers. The raster scanning approach also presents significant challenges for speckle reduction.

Several different types of linear light modulator arrays have been reported in the past, and demonstrations of outstanding image quality have been achieved with both grating light valve (GLV) [2,3] and grating electro-mechanical system (GEMS) [4–6] devices, having resolutions well beyond 1920 × 1080 pixels. Both of these are MEMS-based linear arrays. The GEMS linear array is extremely simple to fabricate (with respect to the DMD), provides very high image quality and enables simple high-performance optical system architectures. The technology offers the potential for lower cost with better image quality.

The following contains a review of the GEMS device construction, the optical systems in which GEMS projection has been demonstrated, and designs that offer a path to still lower cost. We also describe our approaches to uniformity calibration and color transformation.

GEMS LASER PROJECTION

The GEMS modulator is a micro-electromechanical device fabricated on silicon containing a linear array of electrically activated diffractive elements that switch between a reflective mirror-like “Off” state (Figs. 1a and 1b) and a diffractive “On” state (Figs. 1c and 1d).

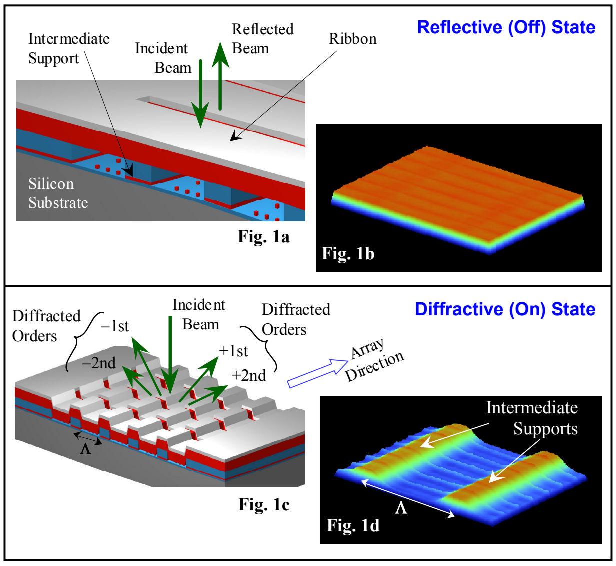


Fig. 1 – GEMS device
Illustration of the GEMS pixel structure (Figs. 1a and 1c), with interferometric profilometry of the ribbon surface for a fabricated device (Figs. 1b and 1d).

Fig. 2 – Image from 115" front-projection prototype
Screen photo with content from scanned motion picture film.

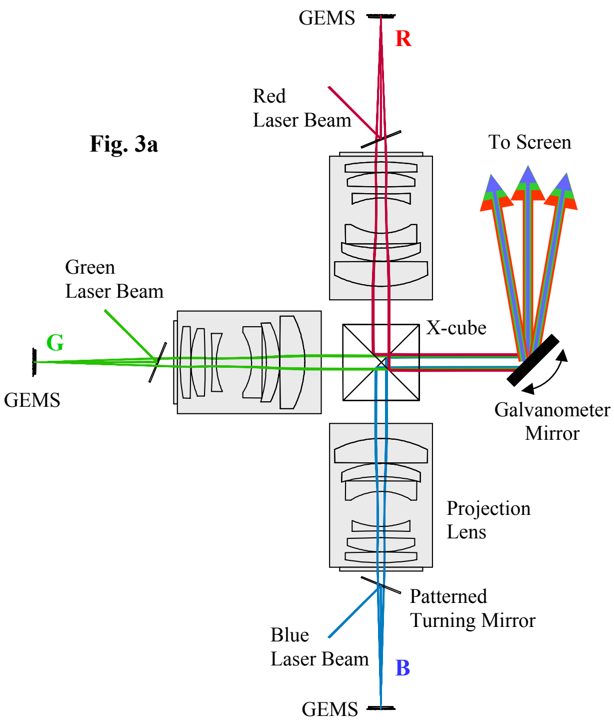
The diffractive grating structure is produced when the MEMS ribbons conform around intermediate supports because of electrostatic force. The GEMS modulator is digital in nature, allowing stable gray level generation through pulse-width modulation of the diffractive state. Though the MEMS ribbons make contact to standoff pillars at the bottom of the deflection, design optimization has solved all stiction issues as evidenced by long-term testing of many devices.

In a display, 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 2D image.

The resultant display delivers high resolution, high native bit depth, wide color gamut, and freedom from motion artifacts and screen door effects. Indeed, our 1080p demonstration system is capable of displaying superb image quality (Fig. 2). The technology also provides a scalable device architecture, large active device area, compact optics, and simple optical design, making it attractive for a wide range of projection display applications.

Figures 3a–3d depict a range of possible laser display system configurations that are enabled by the GEMS device. These simple optical architectures are made possible by the fundamental device structure, specifically, by the large active area with grating period, Λ, oriented perpendicular to the array direction. The straightforward and compact method by which the diffracted orders are separated from the 0^{th} order beams has been described elsewhere [6].

Our demonstration system, shown in Fig. 3a, uses three GEMS modulator arrays and three projection lenses. This configuration was chosen for its ability to



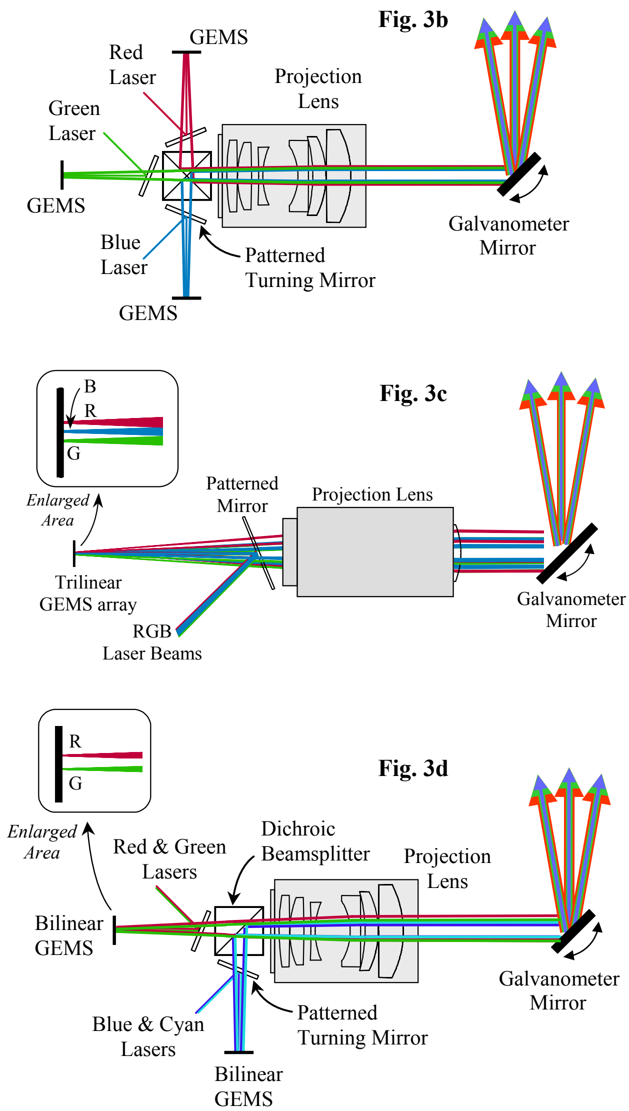


Fig. 3 – GEMS laser display architectures
a) Layout of three-chip three-lens prototype, b) three-chip system design, c) trilinear GEMS array system design, and d) four color system design with two bilinear GEMS arrays.

give maximum system flexibility but would not be a choice for a product. Figure 3b shows the preferred three-GEMS-chip design using a single projection lens. Three-chip architectures, in general, offer complete utilization of available source light, freedom from flicker, and fewer image artifacts, as compared to one-chip color-sequential systems. A unique one-chip solution that combines the simplicity (and low cost) of the one-chip approach with the benefits of the three-chip approach mentioned above is shown in Fig. 3c. The concept uses a trilinear array of GEMS modulators in a single chip, giving a one-chip solution having three-chip performance. A near-term challenge for the trilinear array is interconnecting to the middle linear array of the trilinear set. This could be addressed with high density or buried conductive traces, but would somewhat complicate the device design and fabrication. Full CMOS integration can also provide a solution. An alternative approach is shown in Fig. 3d where two GEMS chips are used. One chip is a bilinear array that is a straightforward extension of our current single array device where addressing would be from each side. The second array could be a single-column GEMS device or another bilinear array that could offer a very simple four-color architecture. Obviously, a system similar to Fig. 3c, but with a single bilinear array instead of a trilinear array, is also possible and could provide an attractive compromise for certain applications.

CALIBRATION

A significant problem with display systems that employ linear array modulators is that even a slight nonuniformity in the projected one-dimensional image produces parallel bands in the two-dimensional scene that are noticeable and objectionable to many viewers, because of the sensitivity of the human visual response to such artifacts. These bands can arise from nonuniformities in the illumination beam and illumination optics, and from variations of the device response along the array. Figure 4a shows a photograph of solid color bars taken from a prototype projection display system without any correction. A calibration system is required to reduce these objectionable horizontal bands in the two-dimensional scene.

The projection display systems of Fig. 3 generate gray levels in the scene from code values in the data stream. In our work, gray levels are determined by using a 2D look-up-table (LUT) to convert code values in the data stream to pulse-width modulated voltage pulses appropriate for actuating the devices. With a 2D LUT, calibration of nonuniformities is possible since there can be a different correspondence between code values and gray levels for each of the modulator elements of the linear array.

There are many strategies for sensing the nonuniformities present in a given GEMS projection display. Because nonuniformities arise from variations in the individual modulator elements as well as the illumination profile, it is best to measure and correct the whole system response. After exploring single detector, linear detector array, and 2D detector array approaches for measuring the display nonuniformity, we chose the 2D array detector method. Reasons include the low cost of these detectors as driven by the consumer digital photographic market, the excellent signal averaging available in certain implementations of the detectors, and their potential for alternate use in projection systems. Specifically, we anticipate that the detector can be useful as a means to sense the presence of an object (human) between the projector and screen in a front-projection system. Though laser irradiation levels are safe in the vicinity of the screen, even if looking back at the projector, it is still desirable to find an approach for enhancing laser safety for large-screen front-projection systems. The 2D image sensor array used for calibration can test, in real-time, for the presence of interposed objects between screen and projector, and this information can be used to blank appropriate portions of the display.

Figure 4a shows an image of an uncorrected color bar pattern being projected on a unity gain screen. A region of the image is shown in Fig. 4b, which has been processed to make the banding nonuniformity more easily visible. For calibration, ostensibly flat field uncorrected images are captured by a 6-megapixel CCD camera. Correspondence of camera data to given GEMS pixels is accomplished by first assigning the detector pixels at the top and bottom of the projected image, for a given column in the detected image data. These correspond to the 1st and 1080th GEMS pixels,

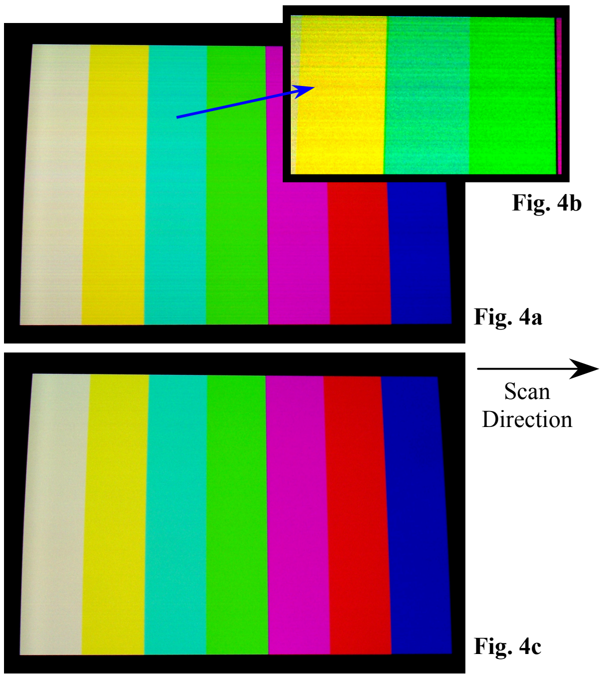


Fig. 4 – Display calibration
a) Uncalibrated image, b) uncalibrated region processed to exaggerate visibility of bands, and c) calibrated image.

respectively. The remaining assignments are made by interpolation. To accommodate any distortion in the projected image, a set of parallel lines is projected onto the screen and is used to obtain a detailed map between camera data and GEMS pixels. The mapping needs only to be done once. For calibration, the camera is used to capture (initially) uncalibrated flat-field data, which is averaged along the scan-direction, using the camera-to-GEMS pixel map. This provides correction factors for updating the 2D LUT. The procedure is performed at full white and a few lower gray levels to adjust for any small variation in the electro-optical response between GEMS pixels.

Typical calibrated maximum brightness target values are around 80–90% of the brightest pixel. Actual measured pixel-to-pixel nonuniformity arising from the GEMS array elements alone are typically within ±5%. The first try at compensation is usually imperfect, and the compensation is repeated wherein the image converges rapidly to a true flat field. The method is very robust owing to the excellent averaging of data made possible by the 2D detector array. A corrected version of the color-bar image is given in Fig. 4c. If needed, the method can allow a nonuniform (unobjectionable) low spatial-frequency center-to-edge fall-off in brightness that can arise from the laser illumination, so as not to unnecessarily sacrifice brightness in the center of the screen.

COLOR

The extreme color gamut available in laser-based displays offers the possibility to represent the world in higher color fidelity than with those displays having less-saturated primaries. Laser-enabled extreme color gamut also makes possible exciting experiences in computer-generated imagery (e.g., for games). An interesting problem occurs when the input signal color gamut is more restrictive than that available in the display. Conventional simple methods for gamut expansion using laser sources have yielded surprisingly disappointing results thus far because of inordinate amounts of hue shift, loss of realistic near neutral and flesh tones, and an overall unrealistic image appearance.

We have demonstrated that it is possible to intelligently expand the chromaticities of the input (ITU Rec. 709) to take advantage of the display gamut without introducing detrimental artifacts. In addition to the usual color space transformation required to accurately represent input signal colors, our demonstration includes an additional transform to accomplish automatic gamut expansion by a user-adjustable parameter. The transform accomplishes a remapping of input colors toward higher saturation values. It is done without changing hue and moves colors toward the gamut boundary by an amount that increases with increasing input saturation values. The hue-independent expansion is achieved by establishing an intermediary color space defined by intermediary primaries (not shown) that allows a simple extension of chromaticity values toward higher saturation, without affecting hue. Figure 5 shows a CIE diagram of the color transformation in u'v' space, for one particular amount of expansion, with arrows indicating the remapping of input to output colors. In general, the amount of color expansion is user selectable. The near neutrals, including flesh tones, are relatively untouched, while input values near the boundary of the input gamut are extended the most to higher saturation values, all without hue change. The procedure can also be applied to the case of greater than three primaries.

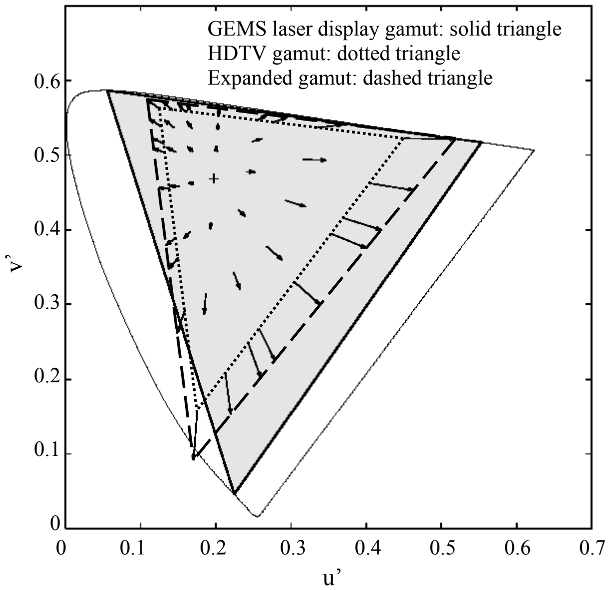


Fig. 5 – Transformation for color gamut expansion
CIE u'v' diagram that shows remapping of HDTV color gamut to an expanded gamut without hue change.

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 1D linear array modulator architecture allows simple and low-cost scaling to full HDTV resolution and beyond. The ultimate commercial success will be dependent upon the emergence of low-cost RGB display lasers.

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