17.3: Calibration of a Scanned Linear Grating Light Valve™ Projection System

R. W. Corrigan, D. T. Amm, P.A. Alioshin, B. Staker, D.A. LeHoty, K. P. Gross, B. R. Lang
Silicon Light Machines, Sunnyvale, CA

Abstract

The Grating Light Valve (GLV™) technology has been used in an innovative system architecture to create a high resolution projected image by optically scanning a linear array of GLV pixels. We will discuss optical and electrical techniques used to optimize the performance of this unique architecture in terms of overall image quality, uniformity and repeatability.

Introduction to the GLV Technology

The Grating Light Valve technology is a means for creating a high-performance spatial light modulator on the surface of a silicon chip. It is based on simple optical principles that leverage the wavelike behavior of light, using diffractive interference as the basis for discriminating between *on* and *off* pixel states. A GLV array is fabricated using conventional CMOS materials and equipment, adopting techniques from the emerging field of Micro-Electromechanical Systems (MEMS). Pixels are comprised of a series of identical mechanical structures, fabricated using very few masks and processing steps. The end result is a unique combination of high performance, reliability, and low cost at production volumes.

Optical Principles of GLV Pixels

A GLV pixel is an addressable diffraction grating created from moving parts on the surface of a silicon chip. A typical GLV pixel consists of an even number of parallel, dual-supported "ribbons" formed of silicon nitride and coated with a reflective aluminum top-layer (Figure1).

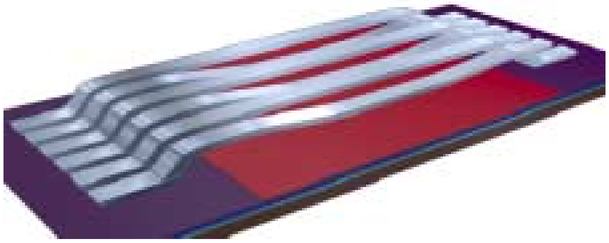

Figure 1: Typical GLV pixel, showing alternate ribbons being addressed.

These ribbons are suspended above a thin air gap allowing them to move vertically relative to the plane of the surface. The ribbons are held in tension, such that in their unaddressed state, the surfaces of the ribbons collectively function as a mirror. When a GLV pixel is addressed by applying an electrostatic potential between the top of the ribbons and the substrate, alternate ribbons are deflected. Viewed in cross-section (as in Figure 2), the up/down pattern of reflective surfaces creates a square-well diffraction grating [7].

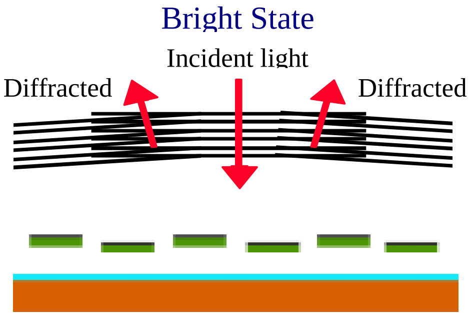

Figure 2: Diffractive (bright) state of a GLV pixel

By varying the drive voltage applied—and thus the grating depth—at each pixel, we can achieve analog control over the proportion of light that is reflected or diffracted.

The Scanned Linear GLV Architecture

The Scanned Linear GLV Architecture was presented for the first time at SID '98 [5]. In contrast to a 2-D array that consists of a physical pixel for every pixel in the final image, the Scanned Linear GLV Architecture consists of a linear array of physical GLV pixels oriented along a vertical column of image data. Once per image refresh, this linear array is scanned across the screen to produce a complete two-dimensional image. During one scan, each pixel writes successive values corresponding to one entire row of image data. In this way, a single scan of the linear GLV array creates the complete image (Figure 3).

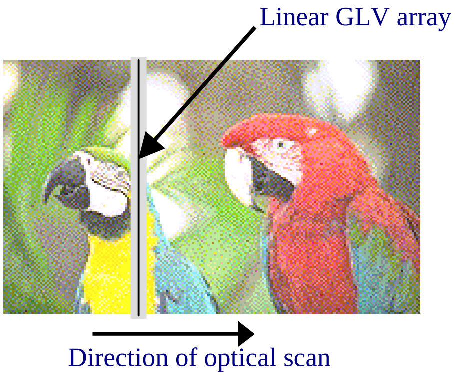

Figure 3: The Scanned Linear GLV Architecture

Presented at Society for Information Display Symposium, 18 May, 1999 San Jose, CA

One main advantage of the Scanned Linear GLV Architecture is that it requires only 1,080 physical pixels to render a complete 1,920 x 1,080 HDTV image. LCD, DMD and other 2-D modulator arrays require the fabrication of more than two million active pixels to achieve the same resolution. Because the Linear GLV Architecture uses such a small array, many GLV modulator candidates can be fabricated on a single silicon wafer with very high yield and low costs.

Modulator Requirements

Considering the fundamental advantages of a scanned linear architecture, why doesn't everyone use one? Such an architecture imposes severe performance criteria on the spatial light modulator used. Specifically, the spatial light modulator must meet three fundamental requirements:

1. It must be capable of extremely fast switching speeds.
2. It must be capable of withstanding very high optical power.
3. It must be capable of rendering gray scale in an analog fashion.

The GLV technology has rather unique performance advantages in each of these areas. Thus, we believe that *only* the GLV technology can support the Scanned Linear Architecture. [1]

Uniformity Challenge for High-End Displays

Image uniformity is an important issue in the design of high-performance projection display systems. Vendors and users of displays often speak of the "bit-depth" associated with each channel of the display. While there is much confusion about the use of such terms, competitive systems today are typically expected to render 8 bits of grayscale per color channel. To consistently resolve these shades of gray, each pixel of the array must maintain uniformity to within a fraction of a least significant bit at all light intensities. The demands of electronic cinema and other high-end display applications call for at least 10 bits of grayscale resolution, implying a need to maintain pixel uniformity to better than ±0.05%.

Achieving such grayscale accuracy presents a serious challenge to the system designer. Precisely measuring intensity variations at the pixel scale is difficult, and the number of factors that can lead to perceptible variations across the image is large. Intensity uniformity is particularly important in a scanned linear architecture because non-uniformities in the imaging system can result in visible striping along the scan direction, which can be more noticeable than the random distribution of noise typical of 2-D architectures.

Sources of Non-Uniformity

Consider the example of a projector based on a 2-D reflective or transmissive array having a 1,920 x 1,080 resolution. The first challenge is to yield greater than two million functional pixels. Assuming that all pixels do function, variations in the electro-optic response of the pixels across regions of the array (often referred to as "mura") can create perceptible blotches on the projected image. Tightening the pixel uniformity acceptance specification at test can incrementally improve modulator pixel uniformity, but only at the expense of reduced yields and increased modulator cost. Variations in the analog or digital performance of the two million independent sets of transistors required to address each pixel can also contribute to localized variability.

Independent of the modulator uniformity, opto-mechanical factors can also lead to imperfections in the image quality of a projection system. Imperfect optical alignment and variations in the illumination intensity at the modulator can create "hot spots" which might move to different areas of the screen, causing noticeable dynamic variation. Registration and convergence of the color channels can vary over time, and even the projection optics may vary in optical performance from system to system. Optical components can become misaligned over time, particularly as the projector is cycled through thermal stress, moved or bumped. The net result of these numerous sources of optical non-uniformity may be noticeable image defects and distortion or the requirement for frequent and time-consuming user re-alignment.

To adequately address these multiple sources of non-uniformity, a practical and effective uniformity calibration system must meet the following criteria:

- Consistently high signal-to-noise ratio (SNR) on the uniformity measurements collected
- Low cost hardware implementation
- Fast and convenient user operation
- Addresses all sources of non-uniformity
- Real-time operation with no light sacrificed from the projected image

Calibration Advantages of the Scanned Linear Architecture

The fact that a linear GLV array uses only a small number of physical pixels greatly simplifies the process of efficiently and accurately measuring the output of each pixel. The linear architecture provides a significant advantage in SNR, since the signal used in the calibration measurement is 2000X brighter than that of a 2-D array. Measuring pixel uniformity in a 2-D architecture would require that two million sets of pixel data be collected. This might be done using a 2M-pixel detector, but such an approach would be expensive and limited by the SNR of the detector array itself. Scanning a low-cost, single-point detector over two million pixels would most likely consume prohibitive calibration time. Assuming one *could* effectively measure the output of two million independent channels, such data would need to be stored in large look-up-tables and significant signal processing hardware would be required to handle the in-stream multiplication required to apply the correction. Lastly, if real-time calibration is required for optimal image quality at all times, an in-situ 2-D uniformity calibration scheme would require a beam-splitter to divert some portion of the light to a detector. This approach implies a direct trade-off between lost light and SNR. A significant amount of light could be lost, as the quality of the correction that can be applied is limited by the accuracy of the data collected. Thus, an in-situ calibration of 2-D arrays is impractical for most applications.

The fundamental difficulties involved with measuring and maintaining uniformity are greatly reduced for the Scanned Linear GLV Architecture. The fact that a 2M-pixel HDTV image uses only 1,080 physical GLV pixels and drive channels greatly simplifies the manufacturing challenge of fabricating and yielding a uniform array (Figure 4). In addition, the nature of the GLV technology and the Scanned Linear Architecture offer a number of unique opportunities for controlling uniformity to within very tight tolerances.

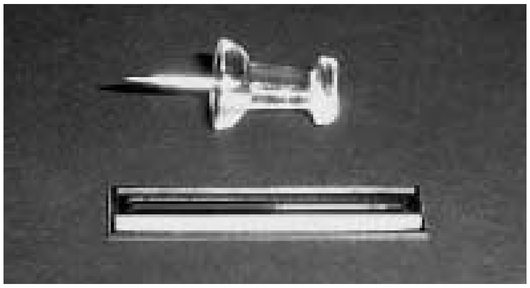

Figure 4: A linear GLV array requires 1/2000th the area of 2-D arrays, making HDTV resolution practical.

First, the inherent GLV electro-optic response (i.e. the fundamental form of the intensity/voltage curve) is remarkably uniform because it is based on a very simple and stable system of electrostatic (attractive) and mechanical spring (restorative) forces. The contributions of shear, torsion, contact, and other forces are negligible. Due to this mechanical simplicity, the GLV response is highly predictable and can be mathematically calculated from relatively simple models. If only a few data points near the peak intensity and maximum slope of the I/V response curve are collected, the rest of the curve can be calculated with a high degree of accuracy. This approach greatly reduces measurement time, and effectively eliminates much of the measurement noise that might be expected if all values along the curve were to be measured (Figure 5).

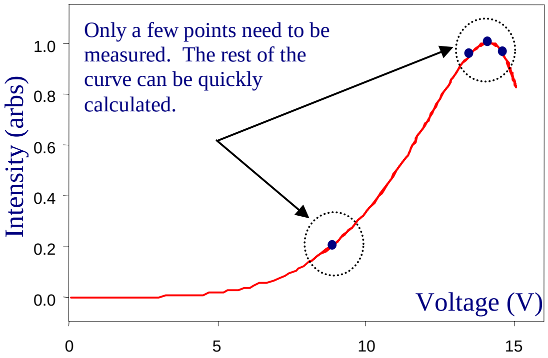

Figure 5: Highly predictable GLV electro-optic response curve simplifies uniformity measurement.

Second, the electronic circuitry required to effect uniformity calibration can be implemented at minimal cost and complexity. Since there are only 1,080 drive channels, only 1,080 values need to be loaded into look-up-tables, as compared with two million required for a 2-D array. Adding the required logic to each pixel's drive circuitry in a 2-D array is typically not feasible because the transistor area located beneath or within each pixel is constrained by the pixel boundaries and/or blocks light. With a linear GLV array, pixel boundaries are not constrained toward the left or right, so additional logic to enhance uniformity can easily be added outside the bounds of the optically active pixel.

Multi-Level Uniformity Calibration System

We have designed a simple and cost-effective calibration system for use within a Scanned Linear GLV projection display. The scanner in this system operates up to 96Hz with a 90% duty cycle and 2% stable overscan time. The basic calibration system consists of 1) a small mirror to which light is directed from the scanner, and 2) a simple integrating sphere with single-point detector. The scanner, which is normally used to scan the image, can also be used to direct light to a mirror outside of the active scan area. The mirror then deflects this light to a low-cost optical detector consisting of a simple integrator and single-point sensor (Figure 6). Pixels are driven to particular voltages, and the output is measured. Digital signal processing techniques are used to improve SNR.

In this system configuration, the detector captures light that has been subjected to all possible sources of image non-uniformity, including the modulator itself, illumination intensity variations, and optical variations in the color-combining and projection optics. Since the data collection occurs downstream of all other system components, all sources of non-uniformity can be corrected. The simple integrator and single-point detector achieve high SNR at very low cost. By exercising pixels in the array, the data necessary to fully calibrate the complete image can be collected quickly without additional equipment or user intervention. The result is a cost-effective system that is capable of several levels of image calibration.

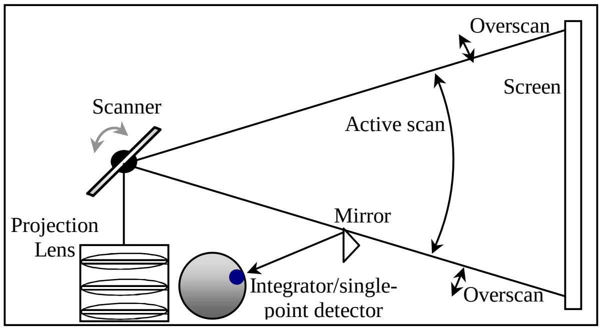

Figure 6: Multi-level uniformity calibration set-up. Light is collected downstream of GLV array and all system optics for complete uniformity calibration.

The first level is *factory calibration*. At the point of manufacturing, a comprehensive system calibration using sensitive instruments under ideal conditions can be efficiently integrated into the standard production test flow. At this point, a device-specific calibration table can be loaded into each system prior to shipment.

The second level consists of a quick, *auto-recalibrate mode*. At the time of system installation, the user can initiate an efficient calibration routine that parks the scanner at the detector and collects the data for every pixel. Since this auto-recalibrate routine only takes minutes to perform, it is practical for a user to conveniently recalibrate the system whenever necessary to ensure highest image quality at all times.

The third level is a unique *real-time calibration mode* that measures and processes calibration data during normal projector operation. Consider a system as illustrated in Figure 6. In normal operation, the scanner slightly overscans the image raster each scan. Rather than blanking the light during this overscan period, light can be directed to the detector. Pixels can then be exercised and calibration data collected. Such a collection scheme can be implemented with zero light loss since the overscan light is free. In this way, a trickle of uniformity data can be continuously collected during normal projector operation. Such data can be processed as a background task and used to continuously maintain optimum image quality.

A Revolution in Image Uniformity

By greatly improving the image uniformity in high-end projection displays, smoothly blended images can be more naturally rendered, and tonal subtleties can be more faithfully reproduced. The real-time calibration that we describe here for the first time meets all of the criteria for an effective and practical in-situ uniformity calibration system: 1) it uses a single-point detection with high SNR; 2) it is low-cost; 3) it supports fast calibration times; 4) it captures light downstream from all sources of non-uniformity in the system; and 5) it supports real-time calibration with zero light loss. Most importantly, this system is capable of producing very impressive results. Real-time calibration is unique to the scanned linear architecture, which in turn requires the unique speed, power density and analog grayscale capabilities of GLV technology. Thus, we feel that the Scanned Linear GLV Architecture offers a number of significant improvements in the area of overall image quality at low cost.

References

[1] D.T. Amm and R.W. Corrigan, “Optical Performance of the Grating Light Valve$^{\text{TM}}$ Technology,” Projection Displays V Symposium, SPIE Proceedings Volume EI 3634-10, San Jose CA, February 1999.

[2] D. Corbin, D.T. Amm and R.W. Corrigan, “Grating Light Valve$^{\text{TM}}$ Technology and Vehicle Displays,” SID Strategic and Technical Symposium, Ypsilanti, MI, September 1998.

[3] R.W. Corrigan, D.T. Amm and C.S. Gudeman, Grating Light Valve$^{\text{TM}}$ Technology for Projection Displays,” IDW, Kobe, Japan, December 1998.

[4] C.S. Gudeman. B. Staker and M. Daneman, “Squeeze Film Damping of Doubly Supported Ribbons in Noble Gas Atmospheres,” Solid State Sensors and Actuators Workshop, Hilton Head, SC, May 1998.

[5] D.T. Amm and R.W. Corrigan, “Grating Light Valve$^{\text{TM}}$ Technology,” SID Symposium, Anaheim, CA May 1998.

[6] D.T. Amm, Report for the DARPA MEMS Semi-Annual Meeting, Contract #DABT63-95-C-0062, Princeton, NJ, July 1997.

[7] D. Bloom, “The Grating Light Valve: Revolutionizing Display Technology,” Projection Displays III Symposium, SPIE Proceedings Volume 3013, San Jose, CA, February 1997.