Grating Light Valve™ and Vehicle Displays

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Abstract

The Grating Light Valve (GLVä) technology offers a unique combination of low cost, durability, and environmental tolerance. We will provide an overview of the GLV technology, and describe a unique system architecture, involving a scanned linear GLV array. We will describe how this architecture can be applied for head's-up displays in automotive applications.

Introduction to the GLV Technology

The Grating Light Valve technology is a means for manufacturing high-performance spatial light modulators on the surface of a silicon chip. Inherent GLV attributes make the technology suitable for a wide variety of imaging applications, ranging from convention hall projection systems, to automotive applications, portable communication devices, printers and optical fiber communications. The technology is based on simple optical principles that leverage the wavelike behavior of light by varying interference to control the intensity of light diffracted from each GLV pixel. 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.

Electro-Mechanics of a GLV Ribbon

A typical GLV pixel is made up of an even number of parallel doubly supported beams, or "ribbons." While pixel dimensions are scaleable, a typical design for a 25 µm pixel (as illustrated in Figure 1) might include six ribbons, each about 3 µm wide, 100 µm long, but only about 100 nm thick. These ribbons are suspended above a thin air gap (typically about 650 nm), allowing them to move vertically relative to the underlying surface. The ribbons are held in tension so that, when not deflected by electrostatic forces, they form a flat surface between the two opposite sets of anchor posts. The ribbons are made of silicon nitride, a ceramic material chosen for its tensile strength and durability. The ribbons are overcoated with a thin layer of aluminum, which functions as both an optical reflector and an electrical conductor.

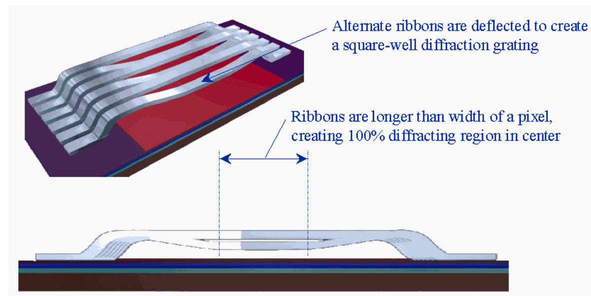

Figure 1: GLV Pixel Showing Alternate Ribbons Deflected (Exaggerated Vertical Scale)

To address a pixel, a potential difference is applied between the aluminum layer on alternate ribbons and the conductive layer in the underlying substrate. This potential difference creates an electrostatic attraction that deflects every other pixel ribbon downward toward the substrate, and thereby creates a square-well diffraction grating. Precise control of the vertical displacement of the ribbon can be achieved by balancing this electrostatic attraction against the ribbon restoring force; more drive voltage produces more ribbon deflection.

Because the electrostatic attraction is inversely proportional to the square of the distance between the conductors, and also because the distances involved are quite small, very strong attractive forces and accelerations can be achieved. These are counter-balanced by a very strong tensile restoring force designed into the ribbons. The net result is a robust, highly uniform and repeatable mechanical system. The combination of low ribbon mass, small excursion (about 1/800 of the ribbon length), and large attractive and restoring forces produces extremely fast switching speeds. GLV pixel switching times have been measured down to 20 nsec—three orders of magnitude faster than any other spatial light modulator we have seen reported.

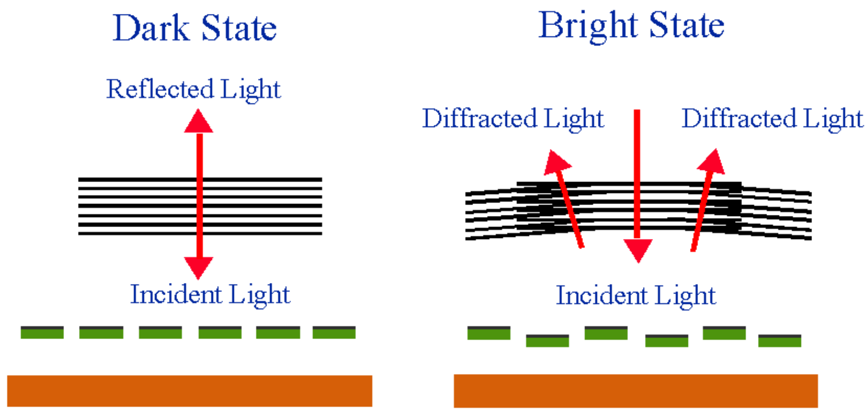

Figure 2: Reflective (Dark) and Diffractive (Bright) GLV Pixel States

Optical Principles of the GLV Technology

When a pixel is not addressed, the undeflected ribbon surfaces collectively form a flat mirror that reflects incident light directly back to the source, as shown to the left of Figure 2. When a GLV pixel is addressed, alternate ribbons deflect downward creating a square-well diffraction grating, as shown to the right in the same figure. Varying the applied drive voltage—and thus the grating depth—at each pixel controls the proportion of light that is reflected back directly to the source, or is diffracted.

GLV devices can be operated in either digital or analog modes, enabling great flexibility in system design and product optimization. Digital operation capitalizes on the GLV technology's tremendous switching speed to achieve shades of gray by alternately switching pixels fully "on" and fully "off" faster than the human eye can perceive. Very accurate grayscale levels are obtained by controlling the proportion of time pixels are on and off. In analog mode, video drivers precisely control the amount of GLV ribbon deflection; pixels are fully "off" when not deflected, and fully "on" when deflected downward exactly one-quarter the wavelength of the incident light. Deflecting GLV ribbons between these two positions creates shades of gray (more precisely, light with the same color as the incident light, but of grayscale intensity).

A Schlieren optical system is used to discriminate between reflected and diffracted light. By blocking reflected light and collecting diffracted light, very high contrast ratios can be achieved. We have measured the contrast of our GLV device at up to 1,000:1 (the sensitivity of our instruments). In an ideal square-well diffraction grating, 81% of the diffracted light energy is directed into the +/- 1st orders. By adding multiple Schlieren stops and collecting more orders, quite practical systems can achieve greater than 90% diffraction efficiency. For example, the device efficiency of a simple (+/- 1st orders only) GLV system, fabricated using 0.6 µm design rules, is the product of diffraction efficiency (81%), aluminum reflectivity (91%) and ribbon/gap efficiency (95%), or about 70% overall.

The Scanned GLV Array (SGA) Architecture

Silicon Light Machines has recently demonstrated [1] a high-performance front projection display system embodying an entirely novel system approach, which we refer to as the Scanned GLV Architecture.

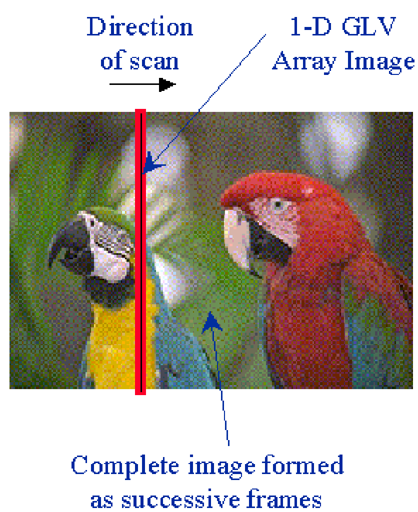

Figure 3:The Scanned GLV Architecture

In the Scanned GLV Architecture, a linear array of GLV pixels is used to project a single column of image data. This column is optically scanned at a high rate across a projection screen. As the scan moves horizontally, GLV pixels change states to rep-

Table 1: Summary of Advantages of the Scanned GLV Architecture
• Very high production yields (and therefore low costs), due to the small active area per die.
• Lower costs, due to the large number of candidate die that can be manufactured per processed wafer.
• Scalability to high resolution – linear scaling instead of geometric scaling as resolution increases.
• Ability to “fine-tune” uniformity after production, due to the relatively small number of active drive channels required.
• Ability to display different aspect ratios using the same display module (for different car makes or models, for example).
• Line-sequential color using switched sources and a single modulator—no color break-up.
• Smaller optics (lenses and dichroics), as only the smaller dimension of the X by Y image raster must be projected.
• Optimal coupling to low-cost laser light sources, as the Scanned GLV Architecture makes effective use of line sources, whereas other approaches require more complex, high-quality beam sources.
• Straightforward integration of drivers and electronics without compromising optical performance, as electronics and mechanics can be “spread out” to the sides of the optically active linear regions.
• Path to full integration of three linear arrays per chip for the ultimate low-cost, mechanically stable RGB projection device.

represent successive columns of video data, forming one complete image per scan. The high inherent switching speed of GLV devices makes a scanned linear architecture, and its many benefits, possible. For example, to create a 1,920 x 1,080-pixel HDTV image like that shown in Figure 3 with a 100 Hz refresh rate, each GLV pixel must change state 192,000 times per second. Thus, each pixel displays video data for 5.2 microseconds, quickly changes state, displays video data for another 5.2 microseconds, and so on.

The Scanned GLV Architecture gives Silicon Light Machines an enormous advantage in terms of modulator cost. To create a 1,920 x 1,080-pixel HDTV image using Scanned GLV architecture, for example, we need to manufacture, interconnect, and address only a single linear array of 1,080 pixels; other spatial light modulator technologies would have to manufacture (with acceptable yields), interconnect, and address more than 2 million pixels. In addition to cost, there are a large number of other advantages that accrue to the Scanned GLV Architecture when compared to current and emerging technologies. These are summarized in Table 1.

GLV Technology and Vehicle Displays

Every successful automotive industry subsystem must meet a unique and stringent set of requirements: it must be low-cost, modular, and reliable over a wide range of temperature, humidity, and vibration/shock. Additionally, automotive display subsystems must be effective in both direct sunlight and near-total darkness. GLV devices inherently meet all of these requirements, making them viable candidates for automotive industry display applications. Figure 4 illustrates one possible application, using a scanned linear GLV array to project a Heads-Up Display (HUD) on a driver’s windshield.

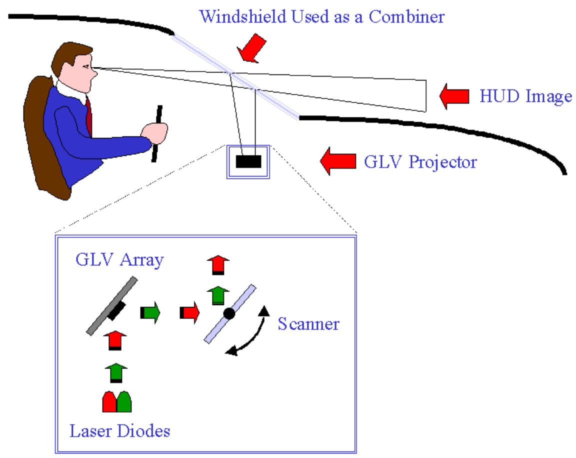

Figure 4: Automotive Heads-Up Display Schematic

GLV devices are low-cost in production volumes because of the simple pixel design, modest processing requirements, and relatively small number of pixels in each linear GLV array. GLV devices are modular because linear arrays are fabricated using industry-standard CMOS processing materials, equipment and techniques, and also because the arrays occupy only a small fraction of the total die area. This allows many other functions to be integrated on the same die, such as system timing, signal processing, video drivers, interface circuitry, etc. We anticipate that the GLV technology's potential for high integration will enable the encapsulation of diode light sources, GLV array, scanner, system electronics and interface circuitry into a single projection module suitable for handling, installation and maintenance by automotive industry personnel.

GLV devices are rugged and dependable. The GLV ribbons, a pixel's moving mechanical elements, are made of silicon nitride, a hard, dense ceramic material grown by a standard LPCVD thermal deposition. Moreover, the ribbons operate with ribbon deflection stresses orders of magnitude below fracture stress limits. Although product life testing is still in progress, individual GLV devices have undergone more than 3×10^{12} ribbon deflection cycles (about 12 years of normal use), and repeated 20 – 100^{o}C thermal cycling, without any measurable performance degradation.

GLV pixels effectively modulate both low- and high-intensity incident light. Reliability tests exposing individual pixels to 30 mW of incident light for several days (roughly equivalent to a 1,080-pixel array modulating 30 W, or a flux of about 5,000 W/cm^2) showed no measurable performance degradation. Moreover, the Scanned GLV Architecture enables the image brightness to be independently controlled at either the light source or the GLV modulator, simplifying the generation of grayscale. This contrasts with emissive technologies, such vacuum fluorescent displays, which must either expand or compress the brightness step size to maintain a consistent grayscale under varying ambient light conditions. Because of their inherent dynamic range, GLV devices are ideally suited for operation over the extremely wide range of ambient light conditions required by automotive display applications.

GLV Laser Light Sources

Like other spatial light modulators, the Scanned GLV Architecture requires that incident light be effectively collected and directed onto the small area of the device itself. For most spatial light modulators, this light must emanate from within a given "acceptance angle" of the normal to the device plane – a "cone" of useful light (light falling on the device that emanates from outside the cone is either wasted or degrades contrast). GLV devices have an acceptance angle comparable to other technologies in one direction, but have a much larger acceptance angle in another direction (perpendicular to the first).

Given its asymmetric acceptance angle and small array size, the ideal Scanned GLV Architecture light source is a bar laser, consisting of a multitude of relatively low-power laser sources, arranged in a straight line, that combine to form a high-power beam. Individual lasers within the bar need not be of particularly high quality, nor exhibit high uniformity from one source to the next, since the modulator effectively averages the variations. Fortunately, such sources exist (for red lasers at the present), and are making rapid progress toward full commercialization and low production costs. Bar laser sources can theoretically couple all of their light onto a GLV array which potentially promises very high efficiency with its attendant lower power consumption, lower heat, smaller product size, and lower cost.

Laser light sources in all the primary visible wavelengths are now commercially available. For example, red and green lasers are found in CD-players, laser pointers, and many other consumer products. Laser technology development has accelerated greatly over the past two years, including significant progress in small blue-violet lasers for optical disk storage. The ultimate solution for compact displays will be the development of red, green and blue Direct Diodes. While red Direct Diode bars exist, the development of blue and green Direct Diodes still involves material science research, and will take several years. However, useful automotive displays that do not require a full color palette (using, for example, red, green, yellow-green, or some combination of these) could be developed much sooner.

GLV Scanner

One component of the Scanning GLV Architecture is a scanner to sweep the modulated light (either horizontally or vertically) across the target projection area. In the front projection HDTV display system reported in [1], we successfully employed a galvanometric scanner similar in design to those used by grocery store bar code readers. In this application, the sweep was horizontal and linear (with a saw-tooth drive signal) with a sweep rate of 120 Hz. Many other scanning mechanisms are possible, each with own set of costs and benefits. Possible candidates for automotive display applications include flexure, rotating polygon, and resonant scanners. Picking the scanner with the appropriate mix of cost, performance and reliability will require further study, preferably in partnership with an automotive systems partner.

Vehicle Display System Design

While there are many feasible GLV system designs for automotive display applications, one promising design framework is shown in Figure 5. This is an adaptation of a portable scanner we successfully designed, built and demonstrated while under contract to DARPA. Here, two or more compact Direct Diode laser sources generate a line-sequential color display using a single time-multiplexed GLV linear array. In operation, a single vertical display line might be illuminated first with its red components of every pixel, then the green components, and finally the blue components, before the scanner moves to the next display line and the process repeats. The persistence of the human eye integrates individual color components into a consolidated image, and since all colors are displayed for every line, there is no image break-up as the eye quickly moves across the display area.

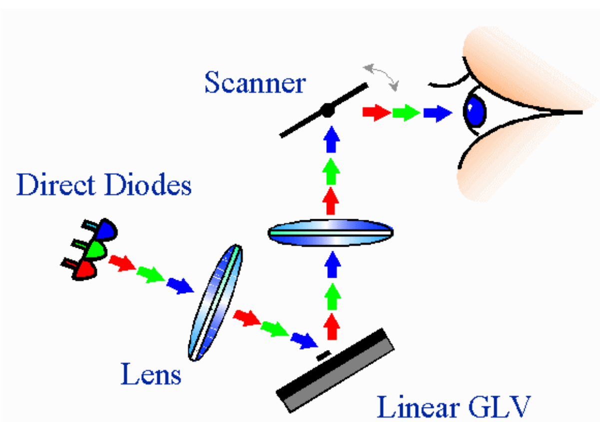

Figure 5: A Possible GLV System Design for Vehicle Displays

Summary

The Grating Light Valve technology, and the Scanned GLV Architecture which it uniquely enables, together provide a solid, stable, demonstrated methodology for generating real-time, high-resolution color images in a wide variety of applications. The GLV technology's inherent low-cost, modularity, reliability, and wide dynamic range make it a viable candidate for information-intensive and reconfigurable automotive display applications. With the right partnerships to develop successful system designs, GLV technology may become the standard for future automotive industry displays.

References

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[2] D. Bloom, "The Grating Light Valve: Revolutionizing Display Technology," Projection Displays III Symposium, SPIE Proceedings Volume 3013, February 1997

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[5] Peter M. Osterberg and Stephen D. Senturia, "M-TEST: A Test Chip for MEMS Material Property Measurement Using Electrostatically Actuated Test Structures", Journal of Microelectromechanical Systems, Vol 6, no. 2, June 1997, pp 107-118.