5.2: Grating Light Valve™ Technology: Update and Novel Applications

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Abstract

The Grating Light Valve (GLV™) technology offers a unique combination of extremely fast switching speed and the ability to withstand very high optical power densities. These and other attributes enable a novel architecture based on a scanned linear array of GLV pixels, which is described here for the first time. This architecture provides a number of advantages over conventional projection display systems that are based on either 2-D spatial light modulators or scanned point systems. These advantages include scalability to very high spatial resolution, natural analog gamma response, high contrast and dynamic range, high optical efficiency, and low cost at production volumes.

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. The GLV technology has characteristics that make it suitable for a wide variety of imaging applications, ranging from front or rear projection systems, to portable communication devices, printers and optical fiber communications. 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.

Electro-Mechanics of a GLV Ribbon

A typical GLV pixel is made up of an even number of parallel doubly supported beams, which we refer to as "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 plane of the surface. The ribbons are held in tension, such that in their unaddressed state, they assume a straight line, forming a flat surface between the two anchored ends. The ribbons are made of silicon nitride, a ceramic material chosen for its tensile strength and durability. The mechanical structure is overcoated with a thin layer of aluminum, which functions as both an optical reflector and an electrical conductor.

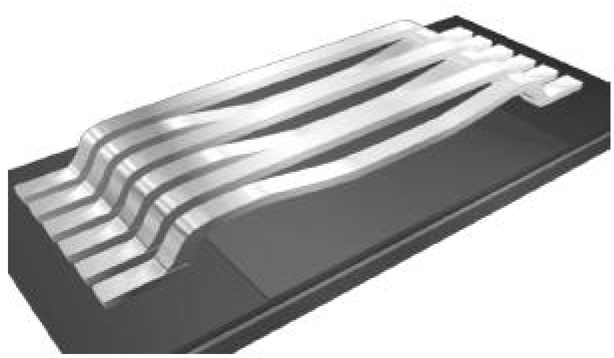

Figure 1: Typical GLV pixel, showing alternate ribbons being addressed

To address a pixel, a potential difference is applied between the aluminum (at the top of the ribbon) and a conductive layer beneath the air gap. This potential difference creates an electrostatic attraction, which deflects the ribbon toward the lower electrode. Precise control of the vertical displacement of the ribbon can be achieved by balancing this electrostatic attraction against the restoring force of the ribbon. When a higher drive voltage is applied, the ribbon achieves equilibrium at a point of greater deflection.

Because the electrostatic attraction is inversely proportional to the square of the distance between the conductors and the distances involved are quite small, very strong attractive forces and accelerations can be achieved. These are counter-balanced by having a very strong tensile restoring force designed into the ribbon. The net result is a robust, highly uniform and repeatable mechanical system. The combination of light mass, small excursion, and large attractive and restoring forces produces an extremely fast switching speed. GLV pixels have been shown to switch in as little as 20 nsec—three orders of magnitude faster than any other spatial light modulator which we have found in published literature.

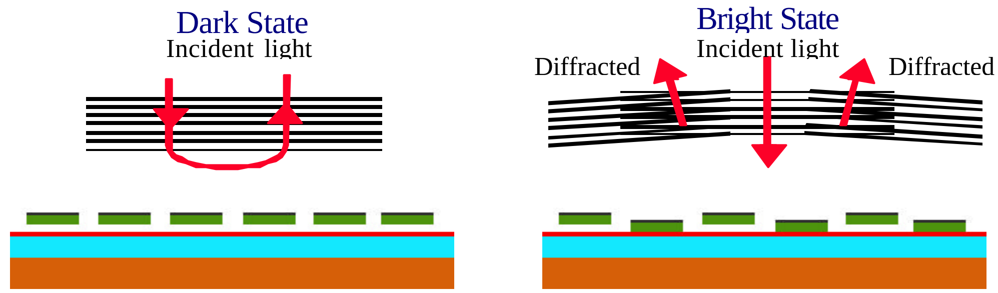

Figure 2: Reflective (dark) and diffractive (bright) states of a GLV pixel

Optical Principles of the GLV Technology

In the unaddressed state, the surfaces of the ribbons collectively function as a mirror. When a GLV pixel is addressed, 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. This grating introduces phase offsets between the wavefronts of light reflected off stationary and deflected ribbons. The functional dependence of the 1st order diffraction lobes is:

$$I_{1st} = I_{max} \sin^2\left(\frac{2\pi d}{\lambda}\right)$$

where I_{max} is the maximum 1st order diffracted intensity (at d = λ/4), d is the grating depth, and λ is the wavelength of the incident light. 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.

A Schlieren optical system is used to discriminate between these two optical states. 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. The gaps between GLV ribbons (defined by minimum lithographic feature) do degrade optical efficiency. The resulting ribbon/gap efficiency for a 25 μm pixel is summarized in the table below.

Ribbon gap (mm)	1.2	1.0	0.8	0.6	0.5	.35
Ribbon/gap efficiency (%)	82	87	92	95	97	98

Thus, for a simple (+/- 1st orders only) GLV system fabricated using 0.6 μm design rules, the device efficiency 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

In early 1997, we began to investigate the feasibility of applying our GLV technology to the problem of high-speed print. In a print system, the media might be scanned past a line of light-modulating pixels. If the image is oriented as shown in Figure 3, at any moment in time the pixels of the array correspond to a single column of image data. During one scan, each pixel writes successive values corresponding to one row of image data. In this way, a single scan creates a complete image. While we are continuing to pursue print applications for the GLV technology, through our investigation into linear GLV arrays, we also proved that the GLV pixels are capable of switching fast enough to apply this architecture to high frame-rate display systems as well.

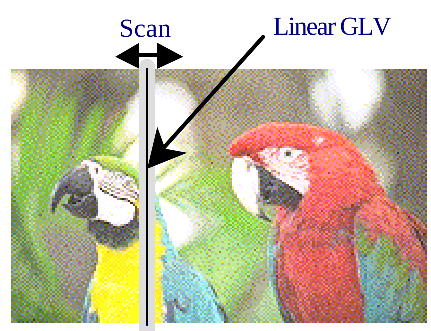

Figure 3: The SGA architecture

Our first demonstration of a display system incorporating a linear GLV array was a relatively low-resolution (320x240) test vehicle in July 1997. In this test vehicle, a simple galvanometric scanner was used near an eyepiece. The optical system was designed such that the rotation of the scanner changed the apparent position of the linear image, creating the appearance of a rectangular image refreshed at the video scan rate (60 Hz). In each column time (1/320th of a frame time, or about 50 μsec in this instance), sequential pulses of red, green, and blue light were directed onto the GLV array. During each color pulse, the GLV pixels were switched on and off in a binary weighted fashion, thereby achieving *line* sequential color. In this test vehicle, the off-the-shelf LCD column drivers we used limited switching speeds to about 2 μsec. With this system, we were able to render very pleasing VGA/4 images with 4096 colors from a single linear array with only 240 active pixels.

Front Projection Display System

Recently, we have built a projection display system to demonstrate the scalability of the SGA architecture to higher levels of performance. In this system, we separate red, green, and blue color components from a white-light laser source. Color beams are directed through line-generating optics onto three linear GLV arrays. Each of the GLV arrays includes 1080 active pixels which correspond to a single column of data from a 1920x1080 (HDTV) image. The modulated light is recombined through a dichroic assembly and projected onto a screen through a projection lens. A galvanometric mirror scans across the image horizontally, such that each GLV pixel paints one row of color channel data for each scan refresh. While this system is only at a bench prototype level, we have been tremendously encouraged by its performance, summarized in the table below.

Parameter	Value
Resolution	1920 x 1080
Contrast	>200:1 ANSI
Convergence	+/- .25 pixel
Refresh rate	Up to 96 Hz
Image size	110” diagonal
Grayscale	8+ bits/channel

Our design goal for this system was a refresh rate of 96Hz, a multiple of 3 or 4 times video or film content of 30 or 24 fps, respectively. At 1920 horizontal resolution, this implies a pixel time of about 4 μsec. Unlike the simpler VGA/4 system described earlier, we elected to use an analog addressing scheme for this system.

Figure 4 shows a plot of diffracted light intensity as a function of applied voltage. Two aspects of GLV analog performance are apparent in this figure. First, there is an extraordinarily close fit between the ideal curve derived from our analytical models and our actual lab results, highlighting the stability and repeatability of the analog performance of these GLV pixels. Second, the shape of this curve conforms closely to a gamma of about 3.0, close to the natural response of the human eye (~2.6). The relative flatness of the curve at lower voltages means that uniform increments of applied voltage result in relatively smaller increments of brightness towards the low-light regions of an image. This type of response is highly desirable for rendering film and video content, eliminating objectionable contouring in low-light scenes common with linear gamma devices. It also allows more efficient re-mapping of video signals onto the GLV-based projection system, preserving more of the dynamic range of the input signal.

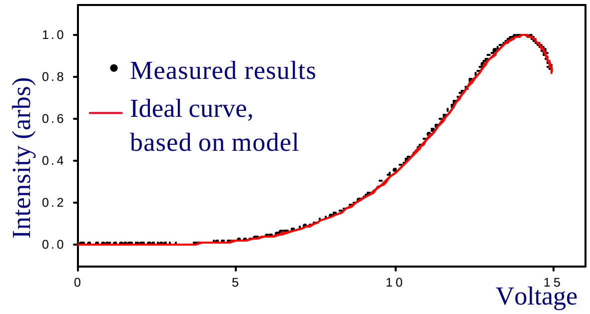

Figure 4: Analog response of GLV pixel

Modulator Requirements for the SGA

To be used as part of a scanned linear array, a spatial light modulator must meet two fundamental requirements. *1) It must be capable of extremely fast switching speeds.* In a high-resolution system, the modulator must switch three orders of magnitude faster than a frame-based array—faster yet if it uses pulse-width modulation to achieve grayscale. We are not aware of other technologies that support this switching speed requirement. *2) It must be capable of withstanding very high optical power*. Because there are several thousand times fewer pixels in the SGA, each pixel must modulate three orders of magnitude greater optical power. For a 10,000 lumen projector, this implies about 20 mW/pixel, a requirement which can be surpassed by the GLV technology, but which we have not seen reported elsewhere. For these reasons, it would seem that *only* the GLV technology could support the SGA architecture, a system approach with significant advantages over either 2-D spatial light modulators or scanned point systems.

SGA Versus Area Array

The demo system we described renders over 2M pixels/field yet uses only 1080 physical pixels. Typically, chip yields are proportional to the inverse power of the active area. With 2,000 times fewer pixels, the SGA architecture has a tremendous yield advantage relative to any technology that must fabricate an entire frame of pixels. A linear array is a small fraction the size of an area array, allowing a greater number of candidates per processed wafer. These fundamentals point to significant cost advantages and further scalability to very high resolutions.

In the case of the GLV technology, the simple design of the pixel requires fewer processing steps than other light modulator technologies. Complete devices require only 7 mask steps. Only the ribbon gap requires tight dimensional tolerances. There are no transistors under the optically active area, so no chemical mechanical planarization is required to restore optically flat surfaces.

An HDTV display system built around an area array requires that 2M individual pixels all function within a narrow band of acceptable uniformity. If one pixel is out of tolerance, it limits the quality of the entire array. Because the SGA architecture uses only one column of physical pixels, it is relatively simple to incorporate into the drive circuitry individual black level and gain adjustments for each pixel. This technique can be used to correct for a variety of non-uniformities caused by system elements, allowing very precise pixel-to-pixel and center-to-edge uniformity across the entire screen.

Our current linear GLV arrays feature ribbons much longer than the pixel width. Only the center portion of each pixel is illuminated, avoiding light losses near the anchor region where the ribbon cannot move. This achieves a pixel with near-zero aperture loss, greatly increasing optical efficiency and reducing required optical power.

In a linear GLV array, each moving ribbon is always between two stationary ribbons. Thus, when adjacent pixels in a linear GLV array are driven to the same value, there is no discernable boundary between the pixels. Along the scan direction, pixel boundaries are also eliminated due to signal timings. The result is a seamless image which, even under close scrutiny, does not exhibit the pixelization (or "screen-door" effect) common to other spatial light modulator technologies.

The horizontal scan of the SGA architecture allows dynamic reformatting of the aspect ratio of the system. An area array must be fabricated in a chosen aspect ratio; any change requires real-time processing to re-map image content and blanking areas of the screen. Light directed to these blanked areas is lost. With the SGA architecture, changing between 1920x1080 and 1280x1024 can be done without re-mapping image data, and with a light loss of only 5%. This compares to a complex spatial transform and light losses of 30% for an area array.

SGA versus Scanned Point

In the SGA architecture, each pixel writes one row of data for each screen refresh. In a scanned point system (a CRT, point-addressed light valve, or a scanned laser system), a single channel must modulate an entire frame's worth of data every refresh. For a high-resolution system, this implies channel bandwidths three orders of magnitude higher than for the SGA system.

To support HDTV at 96Hz refresh in a scanned laser beam system, a 24-facet polygon would have to rotate at an impractical 260K rpm, while maintaining better than 1 part per billion synchronization to the 200MHz modulator that is writing the pixels. Such many-sided polygons are also inefficient in their use of light, as typically the beam must be blanked as it crosses boundaries between facets.

Scanned laser systems also require diffraction-limited sources, which are presently quite costly. The SGA architecture uses a line source, and can tolerate very asymmetric acceptance angles. This allows efficient illumination using simple diode bars and other linear sources with great promise for low cost per watt of optical power.

Where We're Headed

Our current devices are fabricated using a standard CMOS process flow at a nearby foundry. We are midway through the design of custom driver circuits that will be fabricated using this same CMOS production line. When we ultimately integrate these drivers into the GLV array itself, we will have the capability to build longer linear arrays. These can provide the very high resolutions required for electronic cinema, high-grade workstation displays, and other applications.

We also envision fabricating three linear GLV arrays on a single piece of silicon, with the critical tolerances between them defined by photolithography. Given the number of separate optical elements that must be held within critical tolerances in a three-channel color display system, we feel that this path will ultimately lead to the lowest-cost, highest performance display systems available.

References

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