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Optical Performance of the Grating Light Valve Technology

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ABSTRACT

The objective of this paper is to detail the Grating Light Valve™ (GLV™) technology and demonstrate its flexibility in attaining high performance in a variety of optical systems and applications, concentrating particularly on its application toward projection display systems. The GLV technology represents a unique approach to light modulation and offers remarkable performance in terms of contrast, efficiency, switching speed, and cost. The electro-mechanical response of the GLV device can be tuned through various design and operational modes to deliver desired performance for a given application. The design and fabrication of a linear array module of 1,088 GLV pixels is described. This module enables a Scanned Linear GLV Architecture for HDTV projection products. The flexibility of the GLV technology and the Scanned Linear GLV Architecture can support line sequential and frame sequential color, as well as 3-valve color systems. System level optical designs either include embedded scanners to emulate 2-D film source planes or external scanner elements for greater system simplicity. Results with actual projection display systems yield unparalleled on-screen performance, having uniformity greater than 99% corner-to-corner, high contrast, 10-bits of grayscale per color, and no visible pixel boundaries.

Keywords: Grating Light Valve, GLV, diffraction, MEMs, spatial light modulator, Silicon Light Machines, Echelle, SLM

1. GLV DEVICE FUNDAMENTALS

A GLV pixel is an addressable diffraction grating, formed of moving parts on the surface of a silicon chip. Each GLV pixel consists of dual-supported parallel ribbons formed of silicon nitride and coated with a reflective aluminum top layer, as shown in Figure 1. A pixel is turned fully OFF when all pixel ribbons form a flat reflective plane. A pixel is turned ON by electrostatically deflecting alternate ribbons to produce a square-well diffraction grating. GLV pixels can be operated in either digital mode (with alternate ribbon deflections either zero or $\lambda/4$) or analog mode (with alternate ribbons deflecting to positions between zero and $\lambda/4$). A complete description of the basic GLV device has been detailed elsewhere [1-7].

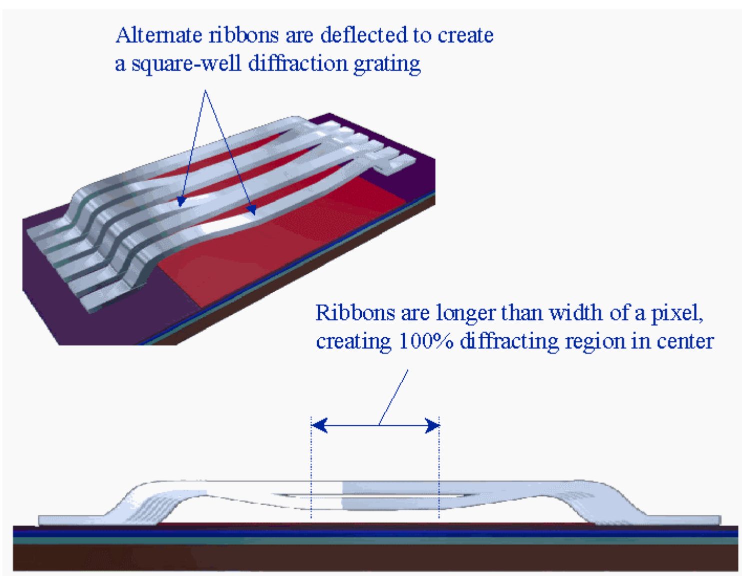


Figure 1: A GLV pixel with alternate reflecting ribbons electrostatically deflected to produce a square-well diffraction grating (vertical deflection greatly exaggerated)

The specific electro-optic response for a GLV pixel is shown in Figure 2. The first order diffracted light intensity is essentially zero when no voltage is applied. Two factors lead to this result. First, most of the incident light is simply reflected specularly by the GLV device, which has a relatively large ribbon width to ribbon gap ratio (~6:1). Second, any potentially diffracting features, such as the ribbon gaps, are expressly created at twice the spatial frequency of the alternate-ribbon ON state. Thus any undesirable diffraction occurs at larger angles, and does not affect contrast in the first order diffraction lobes. The success of this device design is illustrated by plotting the GLV device electro-optic response on a logarithmic scale (Figure 3.) As can be seen, the GLV device performs smoothly and monotonically for well over three decades of intensity. Under idealized conditions, individual device contrast has been measured at over 4,000:1.

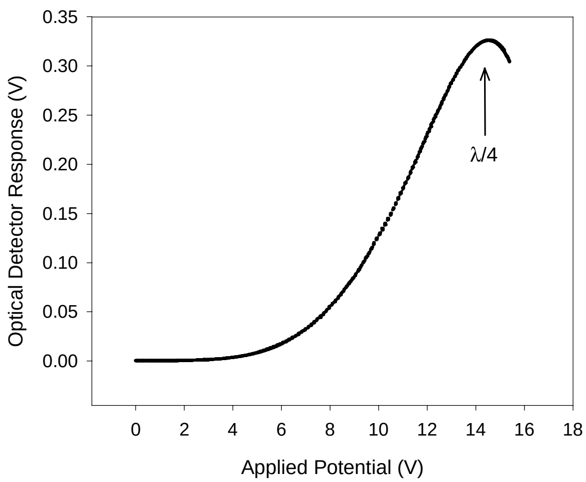


Figure 2. GLV electro-optic response for 1st order diffraction

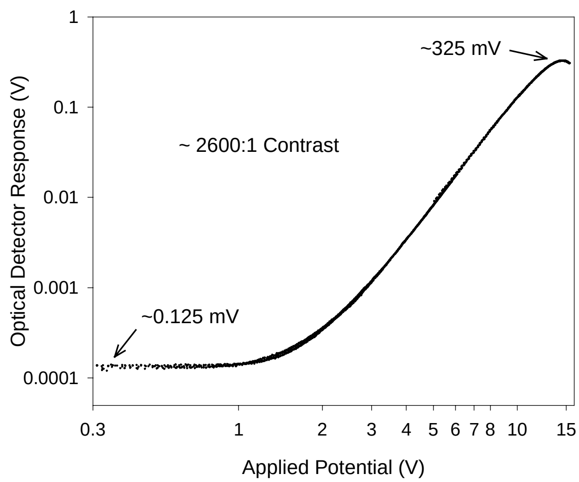


Figure 3. GLV electro-optic response for 1st order diffraction

The switching speed of the GLV device is known to be several orders of magnitude faster than competing technologies. Specific GLV devices capable of switching speeds as fast as 20 nsec have been fabricated [6]. In general, the fundamental switching time of the GLV pixel is related to the resonant frequency of the ribbon design, and determined by such factors as ribbon length, ribbon width, ribbon tension, composition of the surrounding atmosphere, etc. Because the GLV ribbon is a mechanical element, it can be subject to resonance effects that manifest themselves as a "ringing" characteristic following a step excitation. These dynamic effects can be mitigated by the proper design of electronic drive circuitry and by "tuning" the GLV device and its ambient atmosphere such that it is critically damped at its natural frequency. Full knowledge of such parameters permits optimization of the switching characteristic for a particular application.

Figure 4 gives an example of the dynamic response of a GLV pixel driven by a custom driver chip, intended for projection display applications. For analog grayscale operation, the 1 μsec switching time shown is more than sufficient to create a 1,920 x 1,080 HDTV display at a 96 Hz refresh rate.

The efficiency of the GLV device depends on three main factors: the diffraction efficiency, the aperture ratio (or fill factor); and the reflectivity of the aluminum surface. 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 +/- 1st and 3rd orders, quite practical systems can achieve greater than 90% diffraction efficiency. The gaps between GLV ribbons (defined by the minimum feature characteristics of the lithographic tools used to pattern the ribbons) do degrade optical efficiency, but not in the linear manner which intuition might suggest. The fill factor efficiency for a 25 μm pixel (for the +/- 1st order intensity) is summarized in the table below:

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

As an example, 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 fill factor efficiency (95%), or about 70% overall.

Another unique feature of the GLV device is its ability to withstand extremely high optical power densities. The GLV device is composed of simple, stable materials. Specifically, the ribbon material is silicon nitride coated with a thin aluminum layer. The surrounding structures and conductors are silicon, poly-silicon, and silicon dioxide. This material set is very robust by design. The GLV devices are routinely tested to optical power levels of 5 to 10 kW/cm^2 , with no degradation in behavior. Reliability work is continuing to determine the absolute maximum power density. These numbers need to be compared with other modulator technologies that typically quote power thresholds of 1 W/cm^2 or less – several orders of magnitude lower than the GLV devices.

Thus the fundamental GLV technology surpasses many other light modulation technologies in terms of fundamental modulator benchmarking parameters such as contrast, efficiency, switching time, and optical power handling capability.

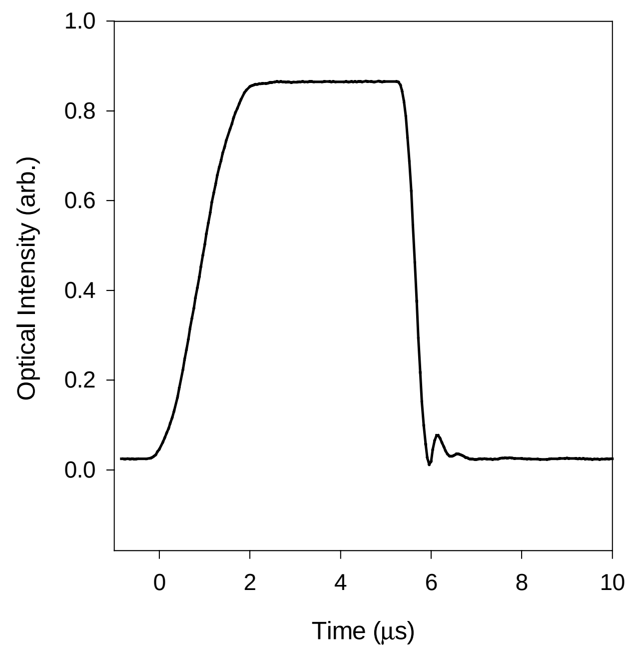


Figure 4. Optical rise time for full-ON to full-OFF transition.

2. THE LINEAR GLV ARRAY

Several of the unique features of the GLV device described above, particularly its fast switching time, high power handling capability, and analog addressability, enable a novel display architecture that offers significant advantages compared to other projection display architectures. A linear GLV array can be used to modulate a single column of image data, while a mechanical scan mirror is used to sweep that column across the field of view. Updating the video data appropriately during the scan can effectively render a full two-dimensional image. The Scanned Linear GLV Architecture was introduced previously [4]. A more complete description of the linear GLV array module and its associated electronic drivers is given here.

The target resolution for the particular display implementation described is the highest-end of the several HDTV specifications – namely 1,920 x 1,080 pixels (1080P). This resolution is achieved using a linear array with 1,080 GLV pixels. Such an array, in module form, is shown in Figure 5. The linear GLV array's 1,088 pixels are at a pitch of 25.5 μm, thus giving a total active area of 25μm by 27.7mm. The linear GLV array is surrounded by four custom driver chips (each with 272 output stages) and assembled into a multi-chip module. The primary function of the driver chips is to provide the digital-to-analog conversion needed for analog grayscale control, and to provide a significant degree of multiplexing so that the module pin count is significantly reduced.

The custom GLV driver chips are very similar in function to standard LCD column driver chips – they receive and present data to the modulator at the line rate. The GLV drivers are designed for line times as short as 4 μs (corresponding to a pixel rate of 250 kHz per drive channel) which is adequate to support a 1,920 x 1,080 HDTV display at a 96 Hz refresh rate. Each driver output is programmable to 256 levels. The shape of the driver response curve is programmable, such that the effective grayscale resolution of the drive circuitry very closely matches the inherent electro-optic response of the GLV device, thus preserving effective grayscale resolution and eliminating banding or contouring at low light levels. In addition, since each video frame is refreshed up to 4 times on the screen, 10-bit grayscale can be achieved by dithering the least significant bits over successive screen refreshes.

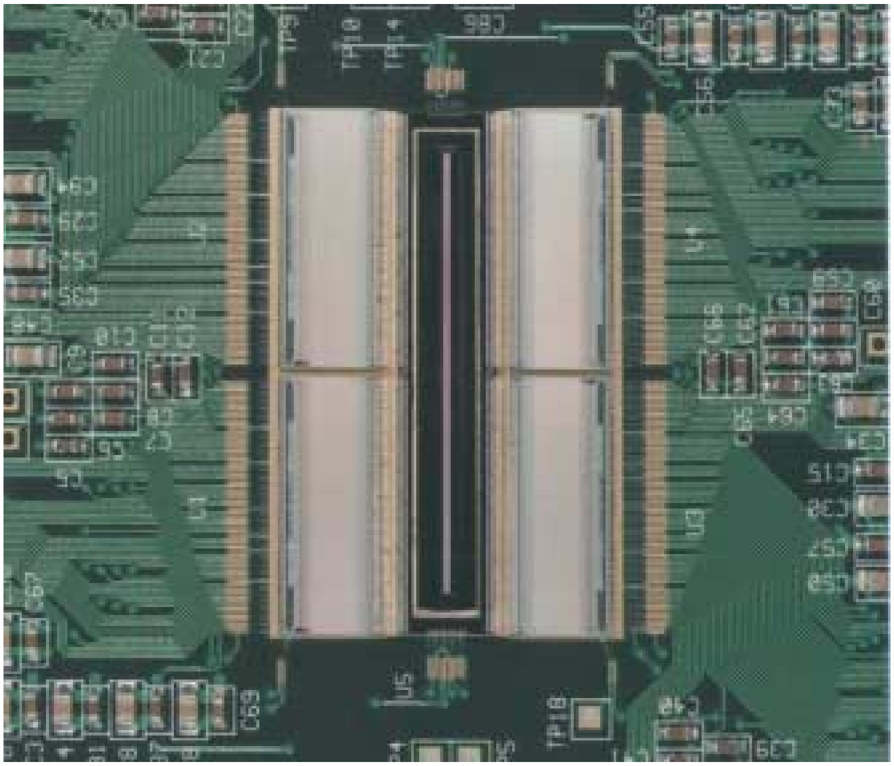


Figure 5. Multi-chip module consisting of 4 custom driver die and a 1,088 pixel linear GLV array. This module can process more than 2 Gbit/sec of video data.

A module operating all 1,080 channels at 8 bits at a line rate of 250 kHz is capable of processing video data at well over 2 Gbits/sec! Currently, the linear GLV array and the custom GLV drive chips used to address them are fabricated in a standard 5 V CMOS foundry, using the same material set and essential process steps. The GLV device itself uses only a small subset of the standard CMOS process, thereby ensuring a smooth path toward full integration of the optical transducer and drive electronics into a single, low-cost, integrated device for high volume applications.

3. OPTICAL SYSTEM ARCHITECTURE

Within the Scanned Linear GLV Architecture, there are several different optical designs that can be implemented to produce fully two-dimensional displays. All of these designs contain the following basic functional blocks: a light source and illumination optics, a linear GLV array, projection optics, and scanning components.

The unique properties of the GLV technology permit several operational modes for creating full color images. Field sequential color with a single linear GLV module is straightforward if suitable red, green, and blue light sources can be switched at three times the image refresh rate. All field sequential color systems, however, can exhibit a disturbing color flash effect as the viewer scans his eyes across the image. A mode of operation unique to the GLV device's capability is line sequential color. Line sequential color again uses a single linear GLV array, but switches the RGB light sources at a rate three times the line rate of the image (several hundred kilohertz for HDTV). Line sequential color takes advantage of the extremely fast switching speed of the GLV device, and overcomes the color break-up problems associated with field sequential color.

For reasons of optical efficiency, high brightness systems are likely to demand continuous light source operation in a three light valve system. Thus, in addition to the function blocks previously listed, color-combining optics may be required, or images can be converged directly at the screen. Two examples of basic 3-valve systems are given in Figures 6 and 7. Figure 6 illustrates an external scanner configuration that has advantages in terms of simplicity and potentially lower costs. An optical relay, either reflective or refractive, can be employed for additional system flexibility, extending working distances and/or providing a secondary image plane for contrast enhancement. Figure 7 illustrates an embedded scanner design whose primary advantage is to provide a 2-dimensional secondary image plane. This type of configuration can essentially emulate the film media plane and allow for simple projection lens inter-changeability and variable throw distances.

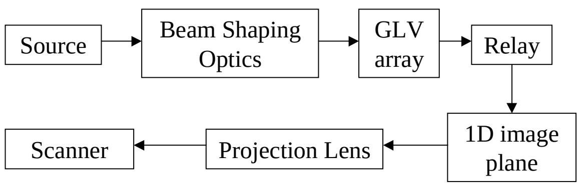


Figure 6. An external, or post-projection, scanner design. The system can be further simplified by omitting the relay, if the secondary image plane is not necessary.

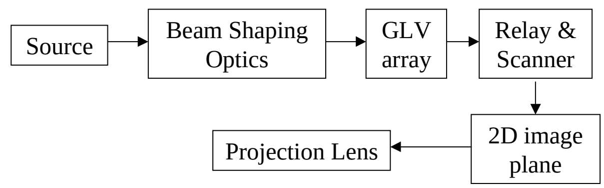


Figure 7. An embedded, or pre-projection scan system.

The illumination of a linear GLV array may appear challenging on the surface: for a 1,080-pixel array, a beam of ~28 mm by 25 microns is needed. In order to maintain good discrimination (contrast) at the Schlieren plane, the rays of light which illuminate a given pixel should have an angular spread somewhat less than the diffraction angle (i.e. a few degrees), in the diffracting direction. (There are no significant restrictions on the angular spread in the non-diffracting direction.) Despite this restriction, if a laser with even modest beam quality is used as the light source, such illumination requirements are readily achieved in practice. Using simple spherical and cylindrical optics, coupling efficiencies greater than 90% are possible. Of course, a complete design involves a number of detailed considerations affecting the uniformity and overfill of illumination along the array. Given the beam profiles typical of commercially produced RGB laser sources, single aspheric elements have been used to achieve excellent illumination uniformity with minimal wasted light.

While the nature of the GLV device does impose a limit on etendue in one dimension, the geometry of a 1,080-pixel array permits efficient coupling of multiple laser beams, or even distributed light sources such as diode laser bars. It is not required that all of the light energy comes from a single, diffraction-limited laser source: a plurality of lower-powered, lower-performance, and low-cost emitters may be used. High coupling efficiencies are achieved with multiple beam, large M^2, or even distributed laser sources. Diode laser bars, for example, represent arguably the highest efficiency means of generating useful light for projection, and offer a path to potentially very low costs. The unique geometry of the linear GLV array allows diode laser bars to be very efficiently coupled into a high-performance projection system, whereas other types of modulator devices may not make effective use of such light sources.

A specific example of illumination optics for a high power laser bar is given in Figure 8. The red laser bar illustrated consists of 24 emitters (each 1 μm high by 40 μm in length) spaced along their long axis at a pitch of ~400μm. A single cylindrical lens is used along the length of the bar for the fast axis collimation, while a perpendicularly oriented cylindrical lens array achieves collimation along the width of the bar. In this system, each of the 24 emitters is imaged to completely illuminate the entire array. Such an illumination design gives good uniformity (essentially the average of all 24 emitters) and also offers protection against potential failure of any given emitter (one emitter failure would result in about a 4% power loss, distributed evenly across all pixels.) Even with this relatively complex optical source, an illumination efficiency of >70% is achievable.

Although a mechanical scanning component is not common to other high-resolution displays, the scanner requirements of the Scanned Linear GLV Architecture do not pose a significant system challenge, as the system needs only scan at the refresh rate, not at the line rate. By orienting the scanner such that the image is scanned horizontally, pixel clock and scanner timing can be adjusted to easily accommodate a variety of image aspect ratios.

Different types of scanners, including rotating polygons, or galvanometer scanners, can be used in the Scanned Linear GLV Architecture. The scanner must operate above ~60 Hz refresh rate in order to avoid any perceptible flicker. The preferred mode of operation is one of "scan-and-flyback", which offers excellent image quality, negligible geometric distortion and good stability from one pass to the next. One issue that can affect the net throughput of the system is the scanner's duty cycle, or dead time during the scanner flyback. However, our work has shown that the scanner duty cycle can approach 90% even at refresh rates of 96 Hz or greater. Several commercial (off-the-shelf) and custom scanners having high MTBF and low cost at volume have been implemented simply and successfully in various display prototypes.

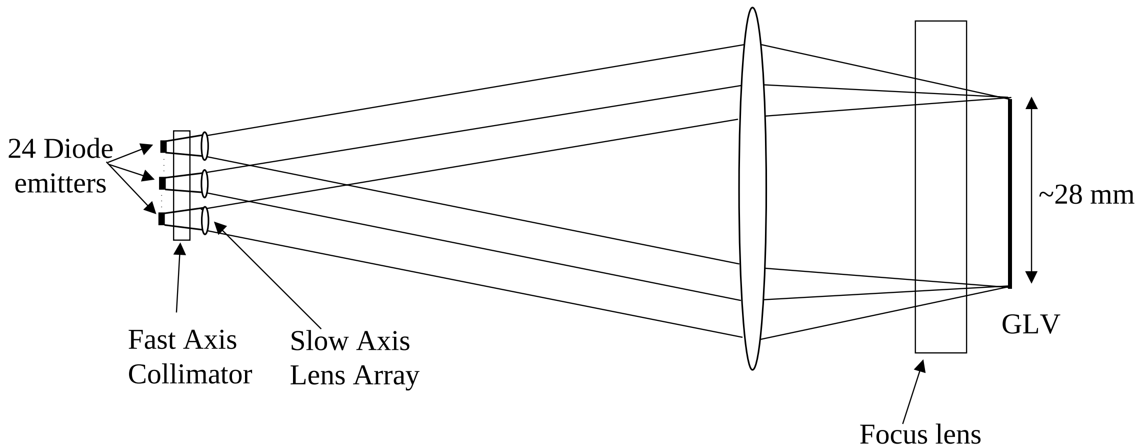


Figure 3. An example of a diode bar illumination design. The diode bar has a total length of about 10mm (24 emitters, each spaced at ~0.4mm).

4. IMAGE QUALITY AND SYSTEM PERFORMANCE

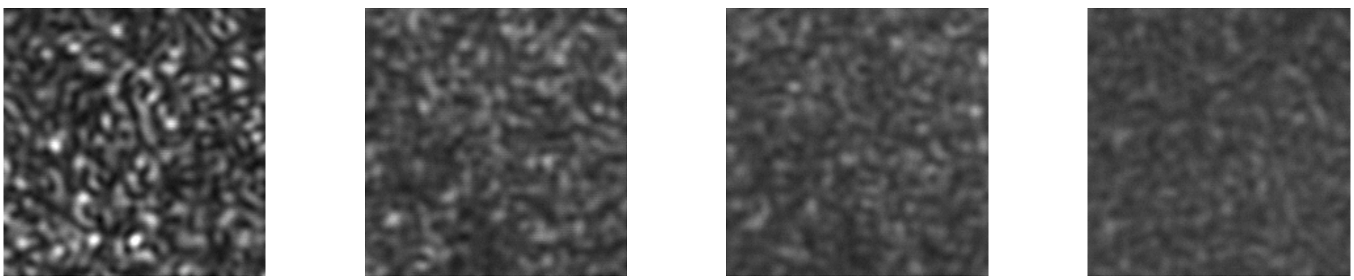
The basic building blocks of the Scanned Linear GLV Architecture have been presented in the previous sections – the light source and illumination optics, the linear modulator module, relay and projection optics and the scanning component. This information lays the groundwork for presenting the system performance, image quality and advantages of the Scanned Linear GLV Architecture.

In an HDTV prototype, a 1,080 pixel array is swept across a screen to create the 1,920 x 1,080 pixel display. One of the most noticeable features of such a display is that there is no visible pixelization (or “screen-door effect”), even upon close inspection. This feature results from two factors. First, along the length of the linear GLV array, there is no pixel boundary due to the nature of the diffraction grating itself. If two adjacent pixels are both activated, then the diffraction grating is simply twice as long, with no visible boundary between the logical mapping of GLV ribbons to drivers. If two neighboring pixels are set to different values, only the transition between the two desired values is discernible. Second, in the scanning direction, the analog grayscale operation (and custom driver design) yields either continuously ON pixels, or smooth transitions between digital levels. If a pixel is switched to a given level and held for an entire line, it simply holds that state for the duration of the line without interruption between pixel boundaries. Elimination of hard pixel boundaries – without compromising addressability or MTF – is an important consideration for the faithful reproduction of film content from digital data.

In the Scanned Linear GLV Architecture, only 1,080 physical pixels and electronic drive channels are required to render an image having more than 2M pixels. This simple fact enables a great deal of flexibility in terms of achieving and maintaining extremely tight uniformity tolerances across the image plane. First, it is a great deal easier to manufacture a highly uniform device having 1,080 electro-optics channels than one having more than 2M channels. Second, it is far easier to accurately measure the individual outputs of 1,080 elements in a linear array than the outputs of 2M elements in a rectangular array. Third, it is quite feasible to implement uniformity calibration electronically on streaming video data. Such calibration can be performed real-time with minimal signal processing overhead, using a relatively small calibration look-up table. We have built systems with less than 1% intensity variability across the screen, and are continuing to improve algorithms for effecting such precision at very low cost and without optical efficiency overhead. This calibration feature will be the subject of a future publication and presentation.

Coherent light from laser sources is known to produce observable interference phenomena. When such light scatters from a rough surface (such as a projection screen), a distribution of random phase shifts is introduced. An observer perceives these phase shifts as a random intensity pattern, appearing as a fine texture overlaying a given image. This phenomenon is referred to as "speckle". Speckle can be numerically characterized by its peak-to-valley intensity modulation (or speckle contrast) and by the coarseness of its texture. Speckle contrast can be reduced by overlaying several independent speckle patterns created within the temporal or spatial resolutions of the eye. Independent speckle patterns can be generated by varying the angle, the wavelength, the phase, and/or the polarization of the scattered light.

Typically, laser-based projection display systems have used rotating diffusers or other motorized optical elements to help reduce speckle. Such approaches may cut into system efficiency, require lower f-number optics, and introduce additional complexity. The Scanned Linear GLV Architecture enjoys a number of intrinsic advantages which mitigate the fundamental causes of speckle, and provide simpler means for reducing speckle to very acceptable levels. As mentioned above, systems using the Scanned Linear GLV Architecture typically use multiple, non-coherent sources, each of which may have relatively short coherence lengths. Such sources have lower initial speckle contrast. The use of linear scanning optics further reduces initial speckle contrast, as each point on the screen is illuminated over a range of angles as the line is scanned. Spatial phase modulation can be achieved using a stationary diffuser element, if the system is designed in such as way that the line of light is scanned through the diffuser. Figure 9 illustrates raw laser speckle and the results of some speckle reduction techniques that were implemented *without introducing additional moving parts.*



(a) **(b)** **(c)** **(d)**

Figure 9. Experimentally measured speckle patterns, with decreasing speckle contrast. (a) High speckle contrast directly from laser source, (b) reduced speckle typical of the Scanned Linear GLV Architecture with no other de-speckle provisions, (c) and (d) further reduction by two additional passive techniques (without the use of a diffuser).

All of the significant factors that impact the overall system efficiency of a scanned linear GLV projection system have been described above. For illustration purposes, consider a single color channel. For a single-beam laser source, approximately 90% of the laser beam can be coupled onto the GLV array. In 1^{st} order light modulation, the GLV linear array approaches 70% efficiency. A projection lens might have 95% throughput. Scanner duty cycle of 90% is achievable even at high refresh rates. The product of these terms yields a color channel efficiency in the 40% to 50% range. To continue this example, commercially available off-the-shelf green (532nm) solid state lasers can produce 10 W or about 6,000 Lumens at the source. With the scanning linear array architecture, this single color channel would produce 2,500 to 3,000 lumens. We have subjected GLV devices to optical flux many times greater than this level. By combining the beams from multiple laser sources, extremely bright projected images can be generated from a single GLV channel without affecting the device reliability or performance.

5. SUMMARY

The Grating Light Valve technology offers unique performance among spatial light modulator technologies. Particularly compelling are its extremely fast switching speed, its ability to be addressed in an analog fashion, and its ability to withstand very high optical power densities. These attributes can be exploited to achieve a novel projection display architecture, which in turn offers a number of system cost and performance advantages over conventional projection display systems that are based on either 2-D spatial light modulators or scanned point systems. Several aspects of the Scanned Linear GLV Architecture have been presented, along with a description of results achieved to date, by a relatively small team, working on laboratory prototype systems, using mostly off-the-shelf optical components. Perhaps the most exciting aspect of the Scanned Linear GLV Architecture is the potential for rapid system improvements, as experienced projection system design teams begin to adopt the essential architecture into their product platforms.

6. REFERENCES

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