Enabling high data-rate imaging applications with Grating Light Valve^{TM} technology

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ABSTRACT

The Grating Light Valve^{TM} diffractive MOEMS device has been successfully used in imaging applications (lithography and display) requiring image data-rates of 1-5 giga-bits per second (Gb/s). However, new applications such as maskless photolithography and high performance displays require larger pixel counts and finer control of gray-scale. This paper discusses the suitability of the GLV device for high data-rate applications. It discusses the factors governing GLV device switching speed and illustrates how these properties are optimized relative to other requirements of the imaging system.

1. INTRODUCTION

The image throughput of an imaging system is determined by modulation rate (switching speed) and pixel count (array size) of the MOEMS modulators. Understanding the design trade-offs between these key parameters is critical for optimizing the system for the specific imaging application. Modulator design governs the architecture of the system (1D vs. 2D), fill factor of the image, and the method for achieving gray-scale (analog vs. pulse-width-modulation). The factors affecting GLV speed include modulator length, width & displacement, effective mass, film tension, damping gas, modulator capacitance, and driver impedance. These factors must be reconciled with other system-level requirements such as physical array size, reflective efficiency, contrast ratio, diffraction angle, driving voltage, and voltage margin. The roadmap for extending GLV device data rate from current levels of ~1Gb/s to anticipated rates in excess of ~100 Gb/s is shown in Figure 1.
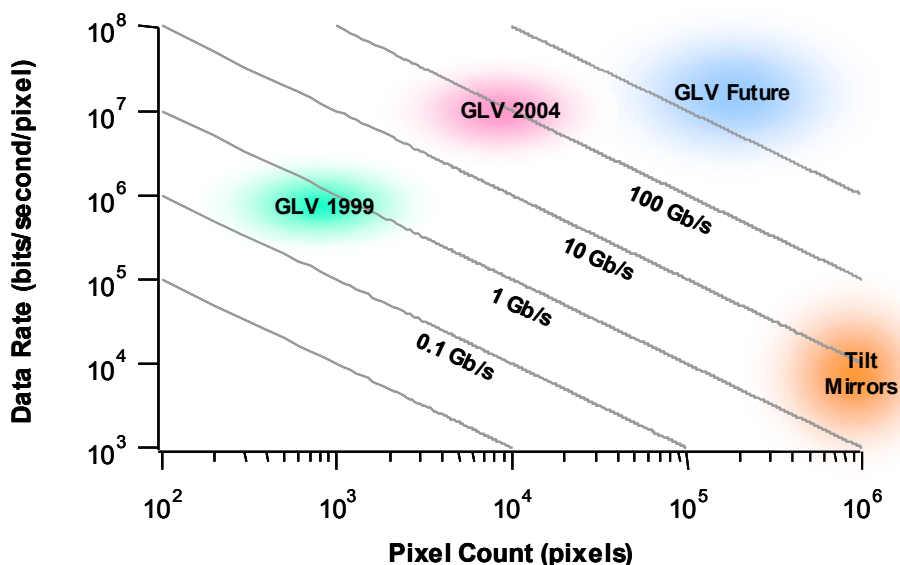

Figure 1. GLV device roadmap: GLV technology is being extended in both modulation and pixel count to achieve the higher data rates. The number of printed pixels per second is tracked on the diagonal lines.

2. GLV TECHNOLOGY FOR HIGH DATA RATES

The Grating Light Valve[TM] is a MOEMS-based programmable diffraction grating [1-3]. The diffractive MOEMS elements are long, tensile micro-ribbons, as shown in Figure 2. The electrostatic deflection of every other ribbon creates a square-well diffraction grating. By applying an increasing voltage to the device, the depth of the square-well grating varies from 0 to $\lambda/4$ (λ is the incident optical wavelength). This is sufficient to continuously vary the GLV device from its fully reflecting state to its fully diffracting state. The GLV device is unique among MOEMS devices in its high speed. The diffractive nature of the device requires only small displacements, a fraction of a wavelength of light, to switch light over large angles. The highly tensile ribbons provide large restoring forces with a very small mass. The net result is that large forces move small masses over small distance very quickly. Combining the GLV device with an appropriate optical system creates a versatile optical modulation technology. The key geometric factors in the ribbon design are illustrated in Figure 2 (right). These factors are the ribbon width, length, and thickness, and the distance to the substrate, which is created by the thickness of the sacrificial (SAC) layer.
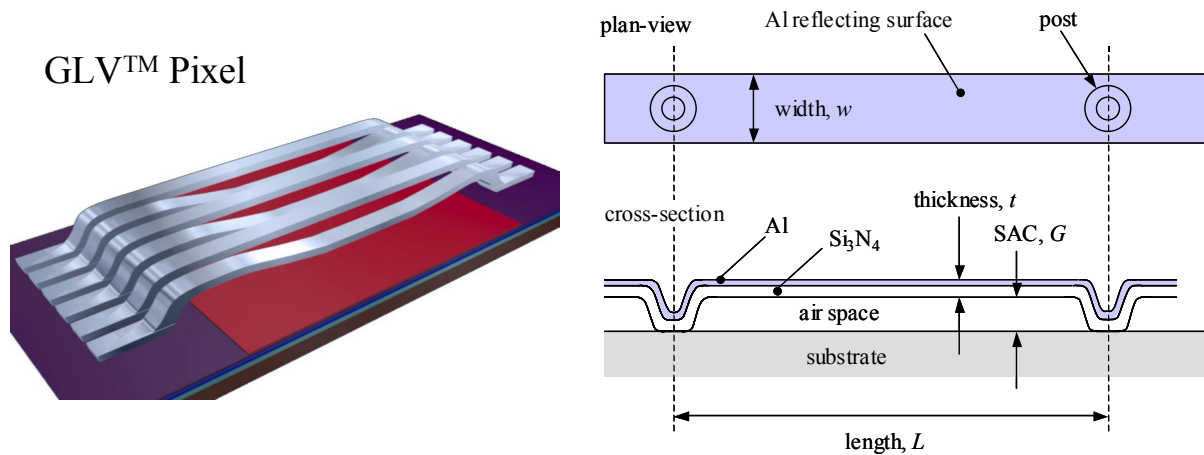

Figure 2. Perspective View of a GLV Pixel (left). Geometric description of GLV ribbons (right). The GLV device is a programmable diffraction grating composed of thousands of micro-ribbons formed from silicon-nitride and aluminum.

A key metric for digital imaging systems is the rate at which image information is delivered to the target. This target may be screen display or a light-sensitive media. Typically, the rate of data delivery is given by the product of pixel modulation rate, multiplied by the number of pixels, multiplied by the number of gray-scale bits. There are several approaches to designing a spatial light modulator imaging system.   One can use a large pixel-count array of relatively slow modulators (DMD approach), or a smaller pixel-count array of fast elements (GLV approach). Obviously, the method of achieving gray-scale is important. For example, if the spatial light modulator uses pulse-width modulation to achieve gray-scale, this directly reduces the usable pixel modulation rate. By capitalizing on the high-speed, analog nature of the GLV device, Silicon Light Machines uses ~thousand element arrays to deliver many millions of gray-scale pixels per second [4-6]. The ability to create a large 2-D image with a 1-D spatial light modulator array allows for a display that is more easily scalable to high pixel counts.   Silicon Light Machines has built a 1080 x 1920 HDTV projection display system, a total of about 2 Mega-pixels, with a 1080 pixel device, essentially providing a 2000:1 ratio of screen pixels to GLV pixels. This 1-D scanning architecture for digital display requires that each pixel deliver 1920 8-bit gray-scale images to the screen in 1/60th of a second -- a modulation rate in excess of 200 kHz.

For printing applications, speed is even more significant. Unlike visual display, modulation speed in printing is not limited by the integration time of the human eye, but rather by the power of the exposure source. The more laser power used, the faster the throughput of the printing, as long as the spatial light modulator can keep up. GLV-based

computer-to-plate printing systems built by Agfa (Wilmington, MA) and Dainippon Screen (Kyoto, Japan) print at rates of 50-100 square cm per second using high-power near-IR laser sources. Clearly, GLV technology is uniquely suited to the aforementioned applications and to future lithography applications.

Silicon Light Machines is also exploring 2-D GLV arrays as a means of addressing the ultra-high data-rates associated with maskless lithography. This combines the speed advantage of the GLV device with the pixel count advantage of a 2-D array. The 2-D geometry obviously increases complexity of the electrical drive circuitry. For this reason, active CMOS switching electronics are being developed.

The current state of GLV technology is illustrated in the following three figures. It can be difficult to characterize the dynamic performance of the GLV device independent of a specific application. The optical rise/fall times, settling time, and contrast will vary depending whether the media is analog or digital (non-linear exposure threshold) or whether the media is moving. A generic method of evaluating the dynamic performance of a modulator is to test the modulation quality as the drive frequency is gradually increased: the modulation roll-off plot. Figure 3 shows the full-scale modulation response of the GLV device as a function of frequency. As shown in Figure 3, modulation fidelity is maintained for driving rates of several MHz.
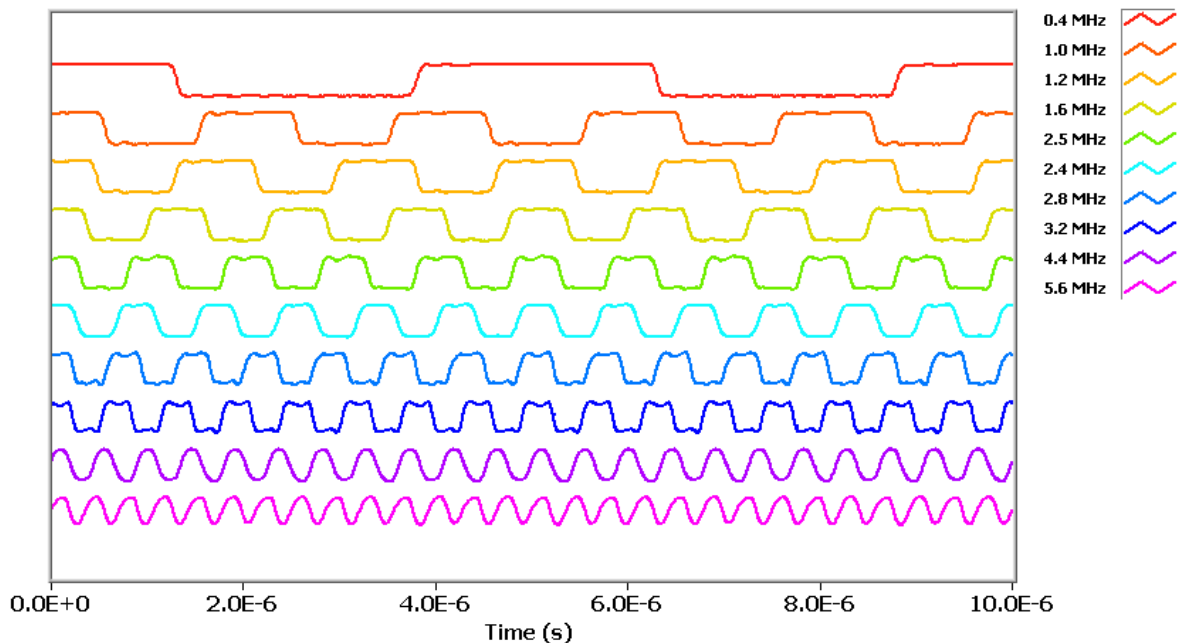

Figure 3. Square-wave pulse trains from GLV device at increasing drive frequencies. Signal is maintained to beyond 5 MHz.

In addition to switching rate, gray-scale control is crucial to most applications. The analog nature of the GLV device allows it to be programmed to specified intensity levels. By comparison, digital modulators use pulse-width-modulation (PWM) for grayscale control, directly eroding the data throughput of the device. Analog gray-scale highlights the value of the GLV device in high-speed applications. Figure 4 illustrates grayscale operation of the GLV device. The plot shows 10 μs optical pulse trains at increasing modulation depths (from 20% to 100%). A related advantage of the GLV device is that extending the bit depth of the display system does not require faster operation of the modulator. On the contrary, it requires only improving the voltage resolution of electrical drive circuitry. Silicon Light Machines currently employs 8 and 10-bit device drivers, although no practical barriers exist to extending bit depth to 12 to 14-bit or beyond.
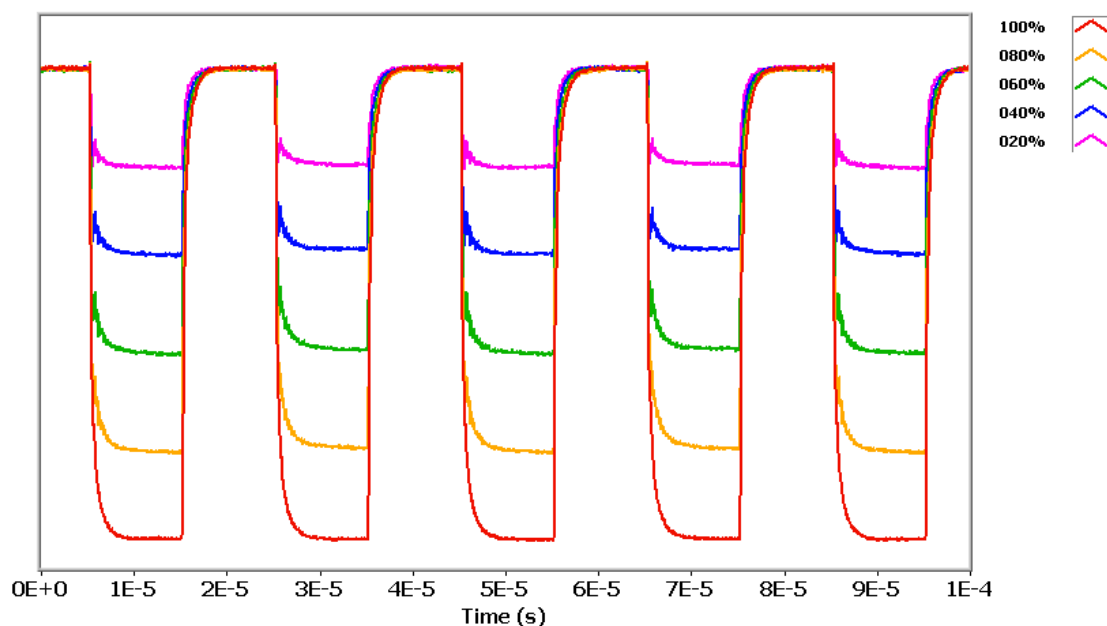
Figure 4. Square wave pulse trains showing the inherent analog gray-scale of the GLV device. Unlike other spatial light modulators, the GLV device does not require pulse-width modulation to achieve gray-levels, allowing it to function in speed-critical applications.

Figure 5 shows a pulse response for a specific GLV ribbon design. The pulse shown is 1 µs long with rise and fall times of ~100 ns. The damping gas in this case is an atmospheric pressure air environment. This design is capable of deflections greater than 150 nm, making it suitable for visible and UV applications. No other optical MOEMS device is known to exhibit the high-speed, analog performance of the GLV technology. The following sections of this paper discuss GLV device dynamics and the design space for the GLV-based systems. The intent is to illustrate how the GLV device can be optimized for high-speed without compromising other system requirements.
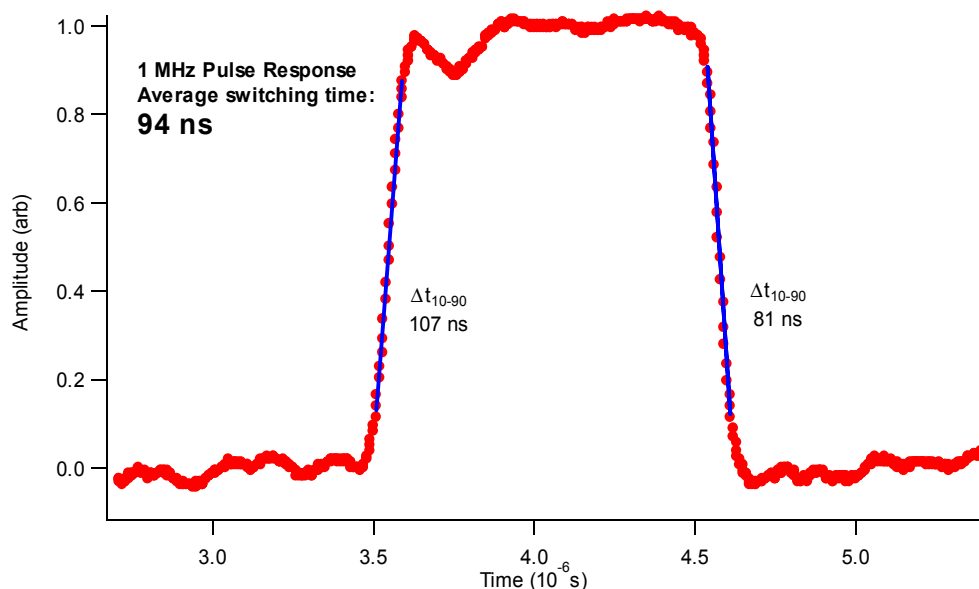

Figure 5. Full dynamic range 1 µs pulse. The response demonstrates ~100 ns switching capability of the GLV device.

3. GLV DEVICE DYNAMICS

3.1 Ribbon Dynamics

Early versions of the GLV technology (circa 1995) relied upon contact between the ribbon and the substrate to provide a digital modulation with an electromechanical holding state or memory [1, 2]. Subsequently (after 1996), the core GLV technology moved to a non-contact, truly analog mode. The ribbons are deflected up to $\lambda/4$ to modulate light intensity through the complete range of fully reflecting (ON), to fully extinguished (OFF). During this $\lambda/4$ deflection, the ribbon maintains a distance of several times that from the substrate. In this mode of operation, the GLV ribbons are well described by a forced, damped, harmonic oscillator [7, 8]. As such, the ribbons are characterized by their natural or resonant frequency and damping coefficient. As in a damped harmonic oscillator, a GLV ribbon response can be underdamped, over-damped, or critically damped, depending upon its design, as is illustrated in Figure 6. High-speed switching devices thus require high resonant frequencies and large damping coefficients in order to minimize ringing artifacts.
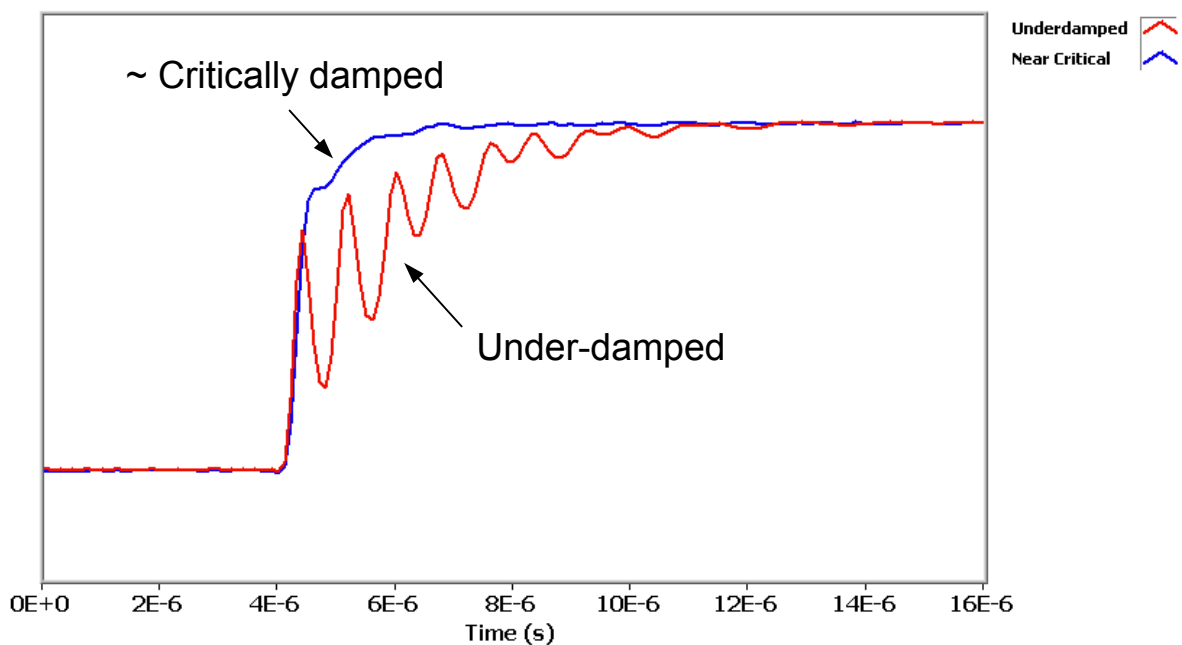

Figure 6. Harmonic Oscillator Behavior of non-contact GLV ribbons showing underdamped and near-critical damping.

3.2 Resonant Frequency

High resonant frequencies are achieved in GLV ribbons by using highly tensile, stoichiometric, LPCVD silicon nitride. This leads to high tensile forces with low mass ribbons, yielding high resonant frequencies. In the plane of the wafers, resonant frequency can be optimized by changing the ribbon length. Figure 7 demonstrates how ribbon length impacts resonant frequency. The plot shows that resonant frequencies > 10 MHz are attainable, which surpasses other technologies by several orders of magnitude. Numerical analysis of the forced harmonic oscillator problem can be used to develop a rule-of-thumb for switching speed and resonant frequency. For a critically damped system, the 10%-to-90% rise/fall time is approximately 1/3 of the resonant period. For a 10 MHz resonant frequency, the period is 100 ns, and by the above rule of thumb, 30 to 40 ns switching times are possible.
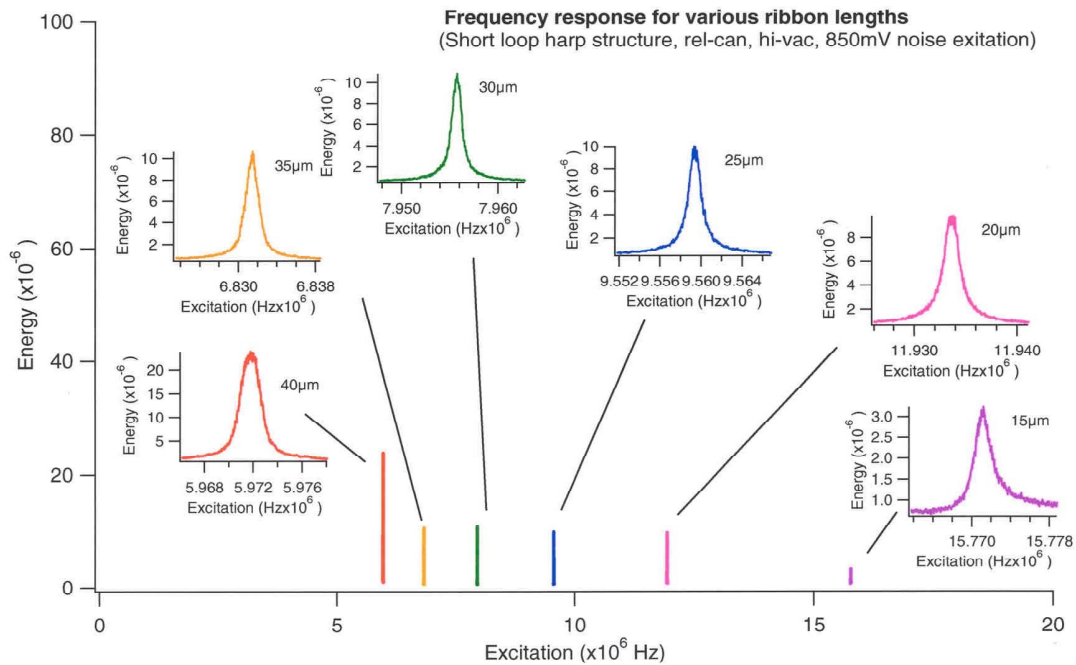
Figure 7. Resonant frequency of several short ribbon designs. Note that resonant frequencies in excess of 10 MHz are feasible.

3.3 Ribbon Damping

In order to exploit these high frequencies, equally large damping must be available. The GLV ribbon damping is determined primarily by squeezed film damping [8, 9]. This damping mechanism depends on the amount of gas trapped during the ribbon movement. This, in turn, depends upon the ribbon width and distance to the substrate (SAC layer thickness). The damping is a very strong function of these dimensions. In addition, the damping depends upon the nature of the damping gas: the gas species, pressure and temperature.

3.4 Other Dynamic Response Issues

The resonant frequency and the damping coefficient go a long way in describing dynamic response of the GLV device, but there are addition factors that must be considered. Although the ribbon motion is well described by the harmonic oscillator, the optical response may not be. In particular, the optical intensity for the GLV device follows a $(sine)^2$ dependence on the square-well depth. Thus, this non-linear optical response can alter the observed dynamic response. For example, the non-linear optical response can cause leading pulse edges to be faster or slower than trailing pulse edges (depending on whether the imaging system uses 0th order 1st order diffracted light). Finally, the electrical impedance or voltage slew-rate will also affect the dynamic response. As shown later in this paper, slope of the drive voltage pulse directly impacts the quality of the resulting optical pulses.

4. DESIGN STRATEGY FOR HIGH-SPEED MODULATION

As mentioned previously, the physical parameters of the GLV ribbons can be optimized to facilitate switching in tens of nanoseconds. However, the speed-related dimensions of the GLV device also impact other aspects of the imaging system. Optimizing the GLV device for speed requires judicious trade-offs with other system parameters. In general, the ribbons cannot be independently optimized for both speed and optical performance. A complete system-level approach is necessary. Silicon Light Machines has designed a broad portfolio of GLV devices and optical systems for applications such as HDTV display, IR-Telecom products, NIR thermal printing, and UV lithography systems. In each case, design tradeoffs were required. Table 1 summarizes this experience in a design space matrix.

The top row of Table 1 lists the physical GLV device parameters related to switching speed. These are: ribbon width (*w*), ribbon length (*L*), ribbon thickness (*t*), and air-gap or sacrificial (SAC) layer thickness (*G*). The left column lists system-level parameters: operation wavelength, efficiency & contrast, incoming data rate, and available drive voltage. Each matrix cell highlights the design relationship between a ribbon parameter and a system requirement. In the following discussion, we examine how each of the physical parameter influences device speed and then examine the inter-relationships between each parameter and the system as a whole. This process is the same followed in designing GLV-based imaging system: individual parameters are adjusted to achieve specific design objectives and then checked against the other criteria to insure satisfactory system performance in all categories.

GLV / System	Ribbon Width w	Ribbon Length L	Ribbon Thickness t	SAC Thickness G
Data Rate	Damping Time	Resonant Frequency	Res. Frequency, Damping Time	Damping Time
Wavelength	Diffraction Angle, Die Size			Snap-down Margin
Illumination, Efficiency & CR	Fill-Factor, # Ribbon Pairs	Illumination		
Operating Voltage		Drive Voltage	Drive Voltage	Drive Voltage

Table 1. Design-space matrix for GLV-based imaging systems. GLV device physical properties are listed on top row and imaging system requirements listed in first column. Matrix cells highlight inter-relationships. Design of GLV-based systems requires adjustments in the GLV parameters (top row) to satisfy all system-level performance requirements (left column).

4.1 Ribbon Width

Because of viscous and squeeze-film damping, ribbon width plays a strong role in determining the maximum pixel modulation rate. In the squeeze-film regime, the mechanical (1/e) damping time of the ribbon is inversely proportional to the square of the ribbon width [8,9]. Figure 8 shows a series of square-wave pulse trains captured from GLV devices of increasing width. It is clearly evident that as the ribbon width increases from 4-6 µm, the quality of the modulation improves as parasitic oscillations are more effectively suppressed in the wider ribbons.
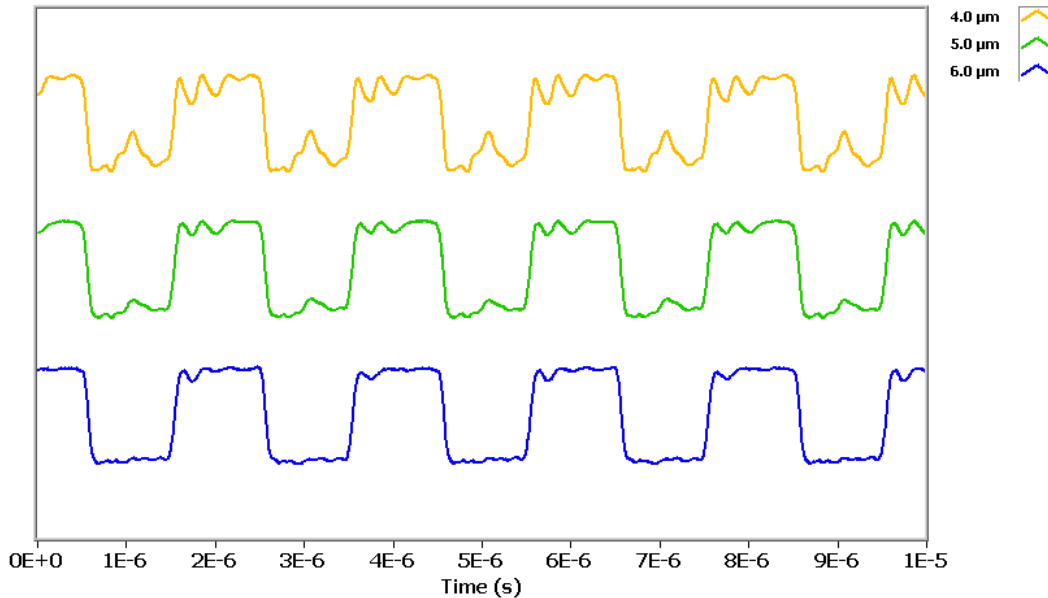
Figure 8. Square-wave pulse trains from GLV devices with increasing width (4 to 6μm). Mechanical overshoots and oscillations are damped more effectively in wider ribbons.

Although ribbon width can be exploited for high modulation rates, Table 1 shows us that this parameter is related to other aspects of the system. In diffractive spatial light modulators, contrast is achieved by Fourier filtering at the transform plane. This requires adequate spatial separation of the 0th from the ± 1st order beams. Braggs law ($n\lambda=2\Lambda\sin\theta$) tells us that fine grating pitches (narrow ribbons) are most effective at resolving the diffracted orders (large angles). Thus, adequate diffraction angle must be balanced against the data rate performance of wider ribbons. Effective Fourier filtering also requires good angular resolution of the diffracted beams (low angular dispersion, $\delta\theta$). This occurs by illuminating a sufficient number of grating periods. For a given illumination spot-size, the tendency is again toward narrow ribbons. In practice, however, Silicon Light Machines has found that adequate contrast is achieved with two to three ribbon pairs. The overall size of the modulator array is also considered in choosing ribbon width. Small die are obviously desirable from a packaging and defect perspective, but less desirable from a ribbon dynamics standpoint. Finally, GLV device optical efficiency is determined in part by the fill-factor ratio (ribbon width)/(gap width). In this case, the system consideration of high optical efficiency works in concert with the beneficial tendency of wider ribbons providing higher speed.

4.2 Ribbon Length
The dynamics of the GLV ribbon are well described by a damped harmonic oscillator [7]. In such a system, response amplitude builds as the drive frequency is increased toward the resonant frequency of the device. As the drive frequency increases beyond resonance, the resulting amplitude diminishes. Since resonant frequency of a GLV ribbon is inversely proportional to ribbon length [10], it is not surprising that shorter ribbons are more effective in high data-rate applications. Short ribbon GLV devices enable higher modulation rates by insuring the ribbons can mechanically follow the drive signal. As the drive signal increases beyond the mechanical time constant of the ribbons, the resulting modulation amplitude diminishes. Figure 9 shows a plot of modulation amplitude versus modulation frequency for a variety of ribbon lengths. The plot shows that shorter ribbons indeed have broader frequency responses. We describe f_{50} as the modulation frequency at which the amplitude of the response is diminished by half of its original value (signal integrity at f_{50} may not be sufficient for practical use, but it nevertheless provides a means of comparing different devices). The inset plot shows f_{50} as a function of ribbon length, showing the expected linear dependence with inverse ribbon length.
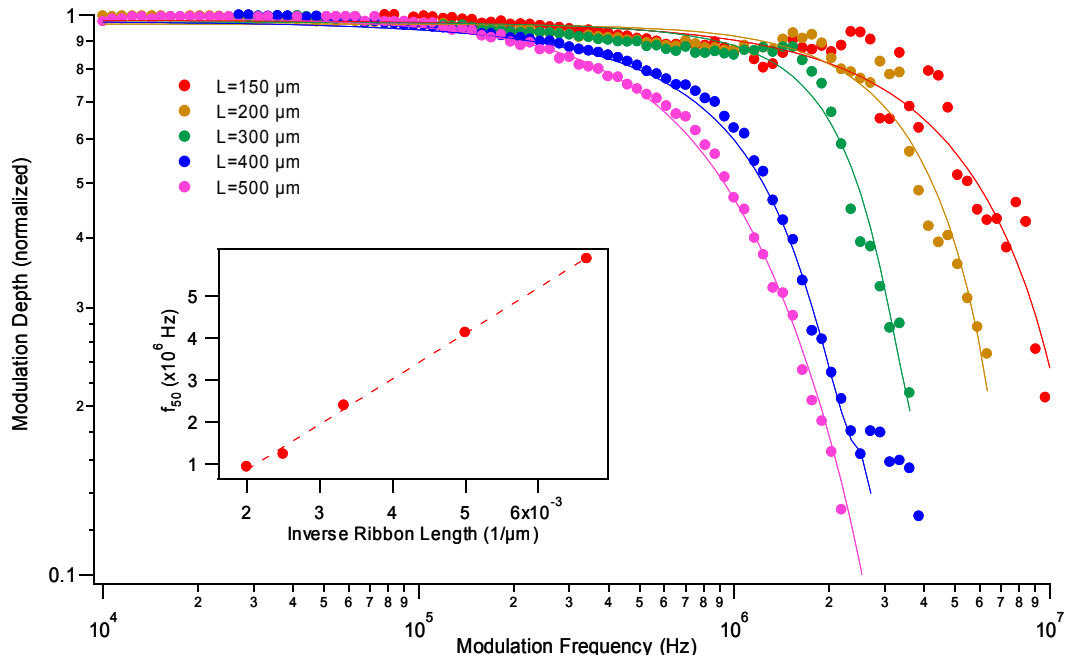
Figure 9. Waterfall plots showing modulation depth vs. drive frequency for GLV ribbons of various lengths. Note that maximum recording frequency (f_{50}) is limited by resonance frequency of ribbon, which is inversely proportional to ribbon length.

While short ribbons are desirable from a frequency response standpoint, Table 1 shows us that that ribbon length is related to two system properties: illumination and drive voltage. Critically illuminating shorter ribbons means more tightly focusing the illumination onto the ribbon array. This translates to faster optics and shorter working distances, which in turn adds additional complexity to the optical system. Moreover, drive voltage is inversely proportional to ribbon length [8]. Typically a fixed maximum voltage is available from the drive electronics, and the GLV ribbon actuation voltage must be held below this value. Clearly, choice of GLV ribbon length must be the result of weighing these competing factors.

4.3 Ribbon Thickness

As shown in Table 1, ribbon thickness influences device speed through resonance frequency and damping time. In a doubly supported string oscillator, resonant frequency is determined exclusively by string length (L), longitudinal stress (σ) and density (ρ) as $\omega = 1/L(\sigma/\rho)^{1/2}$. Since thickness contributes equally to mass and tension, it does not affect resonance. The GLV ribbon is a bi-layer structure composed of a silicon-nitride (Si_3N_4) structural layer covered by an aluminum overcoat. The resonant frequency of this structure is again described by the ratio of film stress to film density, only now using average stress and density of the bi-layer. Depending on the relative stresses and densities of the GLV device materials, increasing one of the film thicknesses can either increase or decrease resonant frequency [10]. For example, the silicon-nitride used in the GLV device is highly tensile relative to the aluminum, while its density is similar. In this case, increasing nitride thickness raises the resonant frequency of the device. Conversely, because the aluminum stress is lower than nitride, increasing the aluminum thickness decreases ribbon resonant frequency.

Damping time is the time required for mechanical oscillations in the ribbon to decay to $1/e$ of their original value. The relationship between damping time and film thickness is straightforward: damping time is linearly proportional to the average mass (density) of the ribbon. Increasing film thickness always increases damping time. Thus, to make fast devices, one should use the minimum practical thickness to achieve a resonance suitable for the application data rate.

Beyond this, the additional mass only degrades damping time.   As with ribbon length, Table 1 shows us that ribbon thickness affects drive voltage.   Actuation voltage scales with the square root of ribbon tension, which in turn is linearly proportional to ribbon thickness. In addition to speed, this is another reason to minimize film thickness.

4.4 Sacrificial (SAC) Layer Thickness

The last parameter listed in Table 1 is the distance between the bottom of the ribbon and the substrate. The sacrificial (SAC) layer thickness (G) plays the strongest role of all parameters in determining the switching speed of the device. Squeeze film theory tells us that damping time is inversely proportional to the cube of SAC thickness [8]. For squeeze film damped interfaces, lateral gas transport (viscous damping) is dominated by vertical compression of the gas layer. This shock-absorber action is extremely effective in damping mechanical oscillations. Figure 10 shows the waterfall plot for two 60 µm long GLV arrays fabricated with two different SAC thicknesses. The f_{50} for 0.6 µm SAC device occurs at over 10 MHz. The inset plot shows an example trace from the 0.6µm device driven a 1 MHz modulation rate. Pulse fidelity is excellent at this frequency, and it is clear that the device could be driven at higher frequencies.
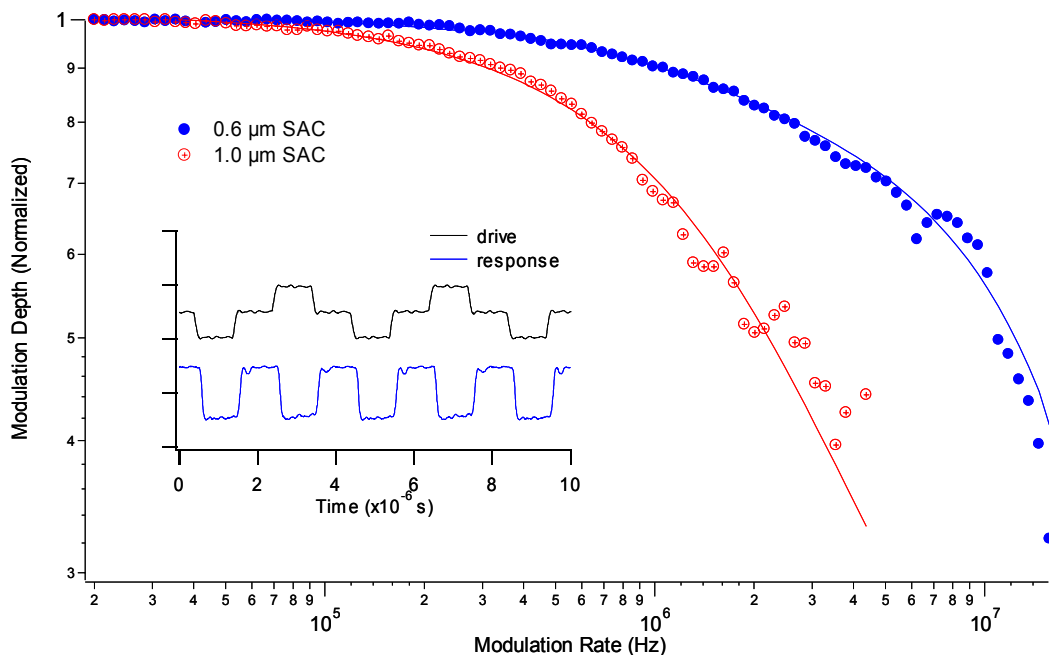

Figure 10. Frequency waterfall plot for 60 µm long ribbons with 1.0 µm (red, open) and 0.6 µm (blue, closed) SAC layer thicknesses. Note the ~10x increase in f50 and improved waveform fidelity at 1 MHz modulation for the thinner SAC device.

Although SAC thickness can be used to very effectively improve the time response of GLV devices, Table 1 indicates that this parameter is again inter-related to two other system parameters. The system wavelength (λ) effectively determines minimum SAC thickness. Since the GLV ribbons must be deflected by λ/4 to achieve full diffraction efficiency, the SAC thickness obviously must scale with wavelength. The GLV device is a capacitive device in which Coulomb forces on the aluminized ribbon deflect it toward the substrate. Elastic restoring forces in the ribbon counter this force.   Because these forces have different dependencies on deflection, snap-down occurs when the ribbon is deflected beyond ~1/3 of the SAC thickness. Silicon Light Machines has determined a safe operating margin is achieved when max deflection is ~1/5 the total gap thickness. This sets the SAC thickness at approximately ~5λ/4. In applications where speed is critical, this rule-of-thumb may be overstepped. In this case, however, careful control of drive voltage and array uniformity is required insure no pixel will snap-down. Table 1 also shows that SAC thickness is related to drive voltage. Drive voltage increases with SAC thickness to the 3/2 power.   In this case the desirable trends toward low voltage operation and fast mechanical damping are aligned.

4.5 Electrical Impedance
The rise and fall time of the electrical stimulus will be determined by the electrical impedance of the system. In the simplest case, this is the equivalent resistance and capacitance of the device. Although not listed in Table 1, this circuit impedance plays an important role in the switching speed of the device. The GLV device has a capacitance value of only a few femtofarads. Usually the system RC time constant is determined by the driver impedance, interconnect resistance and parasitic capacitance. Again, it is a system-level choice to decide how to optimize this impedance. Figure 11 illustrates the various components that need to be considered in the present commercial multichip module.
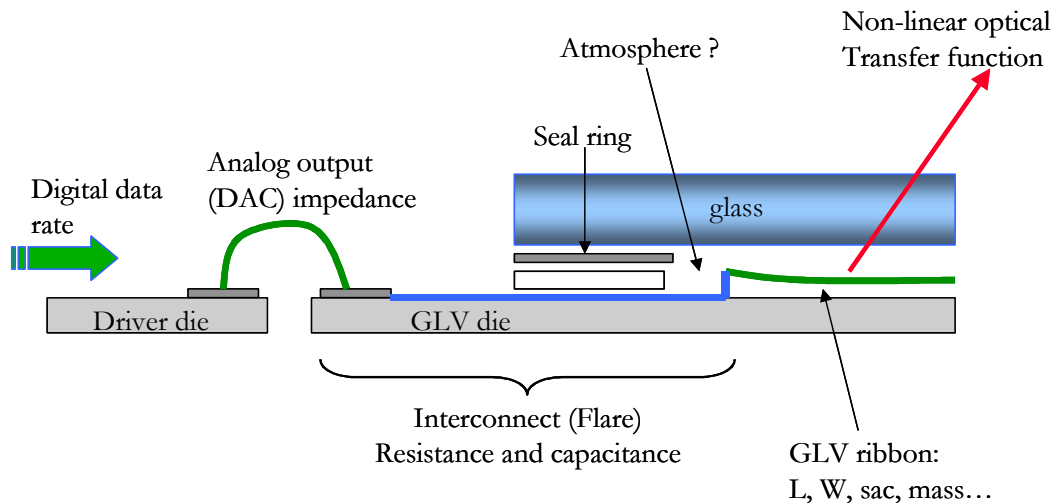

Figure 11. Issues affecting dynamic response

The RC time constant or the slew-rate of the applied voltage does not affect the damping time per se, but it does affect the amount of energy that can be coupled into kinetic energy in the ribbons. This kinetic energy then generates the overshoot and optical signal ringing. Fast rising edges have high frequency components that can excite ribbons at their resonant frequency; slow rising edges have less high-frequency energy and are less efficient at exciting those oscillations. Thus, slower slew rates can reduce the ringing amplitude. However, if the electrical slew rate is too slow, it dominates the dynamic response time of the system, and the full capability of the GLV device will no be realized. Figure 12 illustrates this effect.

4.6 Packaging Gas
The effect of the packaging gas has been described elsewhere [8, 9]. Higher viscosity of the gas will remove kinetic energy from the ribbons more quickly than lower viscosities. Thus, increased damping can be achieved through the use of higher pressures, or generally, heavier gas species. Often, packaging requirements preclude high positive pressures, so this has limited practical utility. However, the choice of species is important and generally easy to implement. Figure 13 illustrates the case of Xe gas used for damping, in comparison to room air. Ribbons of 3.5 μm wide are excited through a tone burst in 1 atmosphere of air and xenon respectively. The resulting damping curves illustrate that xenon reduces the magnitude of the optical signal oscillation by a factor of two and reduces the 1/e damping time damping time by 30% relative to air.   It is important to note that the optimal damping gas for switching speed may not be the best choice for thermal conduction. Silicon Light Machines currently produces a commercial product for high power thermal printing. Operating at 80 watts of infrared light requires specialized gas mixtures with high thermal conductivity. This is yet another example of balancing device speed against other system-level concerns.
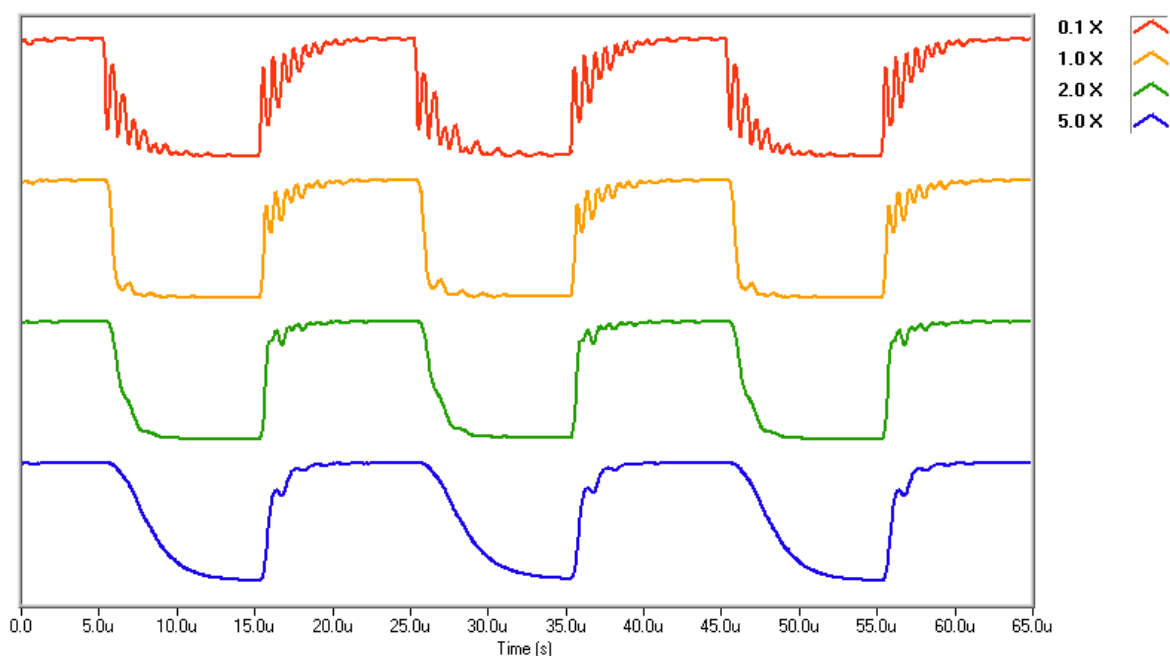
Figure 12. GLV device pulse trains with increasing circuit impedance. Mechanical ribbon oscillations are strongly excited if circuit impedance is low (fast rise time). Increasing impedance softens pulse edges. This reduces mechanical oscillations, but also degrades transition times.
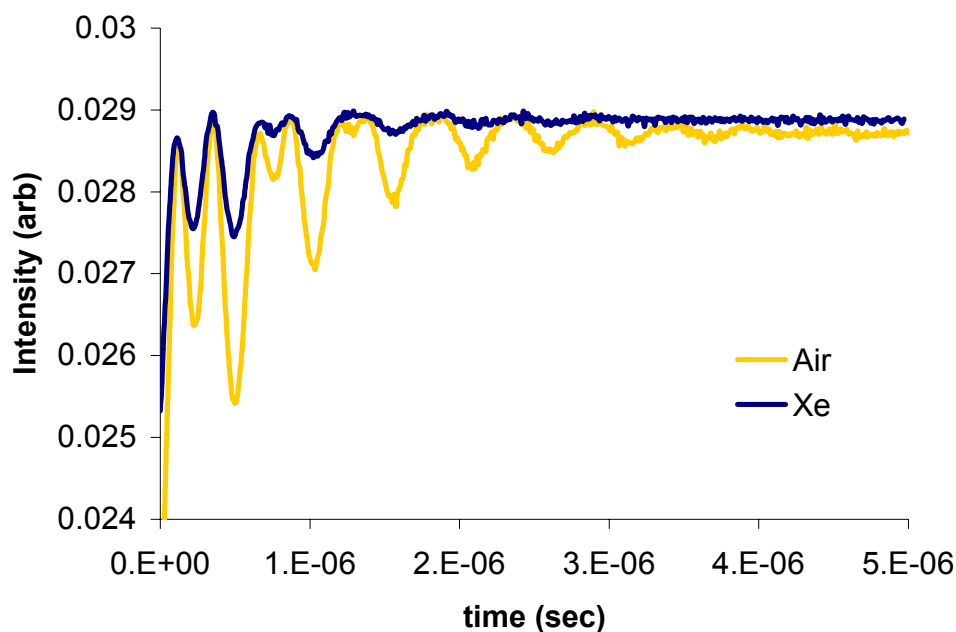

Figure 13. Comparison of air and Xe as a damping gas. Xe provides a 2X reduction in the amplitude of the parasitic oscillations and a 30% improvement in damping time relative to air.

5. CONCLUSIONS

The inherent high switching speed and analog gray-scale capability of the GLV device make it uniquely suited for high speed imaging applications.   Current print and display applications are operating at data rates ranging from 1-5 Gb/s. Through modest increases in pixel count and full exploitation of the switching speed capability of the GLV device, the technology can be readily extended to data rates > 100 Gb/s.

The dominant factors determining switching speed of any MEMS device are the resonant frequency and the damping factor.   Physical parameters of the GLV can be straightforwardly adjusted to optimize for switching speed, although tradeoffs must be made to ensure performance of all aspects of the imaging system. The data presented here show GLV ribbons can be designed with resonant frequencies > 10 MHz, and that the GLV can routinely switch in < 1 µs with transition times of ~100 ns.   Through optimization, the GLV should support 100 ns pulses with 30 ns transition times. These rapid switching rates can easily support pixel modulation rates of ~2 to 5 Mega-pixels/s per modulator element. The ability to operate at such a high rate requires only modest die size and pixel count on of the order of 25,000 to 50,000 to reach a rate of 100 Gb/s. This is clearly an advantage over other system architectures which require tens of millions of pixels to approach a similar throughput.

REFERENCES

1.   O. Solgaard, F. S. A. Sandejas, and D. M. Bloom, *Deformable grating optical modulator*, Optics Letters, vol. 17, pp. 688-690 (1992).

2.   R. Apte, F. Sandejas, V. Banyai, and D. Bloom, *Grating Light Valves for High Resolution Displays*, Solid State Sensors and Actuators Workshop, June (1994).

3.   D. Bloom, *The Grating Light Valve: Revolutionizing Display Technology*, Projection Displays III Symposium, SPIE Proceedings Volume 3013, Ming H. Wu, Ed., Proc. SPIE 3013, 165-171 (1997).

4.   D. T. Amm and R. W. Corrigan, *Grating Light Valve Technology: Update and Novel Applications*, SID International Symposium Digest, **29**, 29-32 (1998).

5.   D. T. Amm and R. W. Corrigan, *Optical Performance of the Grating Light Valve Technology*, SPIE Proc. **3634**, 71-77 (1999).

6.   S. R. Kubota, *The Grating Light Valve Projector*, Optics & Photonics News, pp 50-53, September (2002).

7.   *Vibrations and Waves*, A. P. French, W.W. Norton & Company Inc., New York, 1971.

8.   *Microsystem Design*, S. D. Senturia, Kluwer Academic Publishers, Boston, 2001.

9.   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), pp. 288-291, June (1998).

10. A. P. Payne, B. Staker, C.S. Gudeman, M. Daneman, and D.E. Peter, *Resonance measurements of stresses in Al/Si3N4 micro-ribbons*, in *MEMS Reliability for Critical and Space Applications*, SPIE Proceedings, vol. 2880, pp. 90-100 (1999).

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