Presented at Photonics West 2004 - Micromachining and Microfabrication Symposium
January 26, 2004, San Jose, CA, USA

Overview and applications of Grating Light Valve™ based optical write engines for high-speed digital imaging

(Invited)

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ABSTRACT

The Grating Light Valve™ (GLV™) is a diffractive MOEMS spatial light modulator capable of very high-speed modulation of light combined with fine gray-scale attenuation. GLV-based products are field-proven in a variety of applications. In this paper, we describe the GLV device, its structure, theory of operation, and optical performance. The versatility and speed of the GLV device are described. We explain how the GLV device is integrated into an optical write engine to create a complete digital imaging system. In addition to the MOEMS die and drive electronics, the light engine also comprises illumination optics, Fourier filter, and imaging optics. We present current applications of the GLV device for high-resolution displays, and computer-to-plate printing, as well as future plans for digital imaging applications opened up by the unique properties of this diffractive MOEMS technology.

1. INTRODUCTION

The Grating Light Valve device is a unique member of the family of micro-opto-electro-mechanical structures (MOEMS) products employed for light switching and attenuation in variety of applications[1]. The GLV device switches and modulates light intensities via diffraction rather than by specular reflection, polarization-modulation, or interferometry. There are a number of distinct advantages to this unique method of light-intensity manipulation: high-speed modulation, fine gray-scale attenuation and scalability to small pixel dimension.

The GLV device is built on a silicon wafer and is comprised of many parallel micro-ribbons that are suspended over an air gap above the substrate. The ribbons are electrically conductive so that when a voltage is applied to a ribbon it is deflected downward toward the substrate. If alternate ribbons are deflected downward, then the GLV device forms a square well diffraction grating, as depicted in Figure 1.

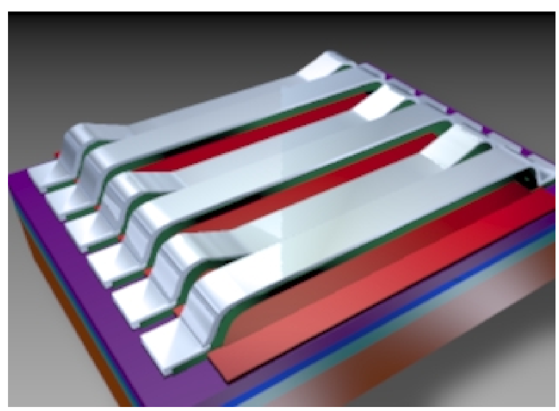


Figure 1. The GLV Device with alternate ribbons deflected to form a dynamic diffraction grating

The ribbons are highly reflective so that when ribbons are co-planar, the GLV device acts like a mirror and incident light is specularly reflected. When alternate ribbons are deflected, the angular direction in which incident light is steered from the GLV device is dictated by the spatial frequency of the diffraction grating formed by the MOEMS ribbons. As this spatial frequency is determined by the photolithographic mask used to form the GLV device in the CMOS fabrication process, the departure angles can be very accurately controlled, which is obviously quite useful for optical switching applications.

The linear deflection of the GLV ribbons is quite small, in the hundreds of nanometers, with no physical contact between moving elements, thus avoiding mechanical fatigue, wear, and stiction failure modes (common in other MOEMS devices) which can significantly reduce the device lifetimes.

There are no physical boundaries between switching/attenuating elements in the GLV array. The length of an individual switching/attenuating element in the array is set by which ribbons are driven together electronically. Thus one single pair of ribbons can form a switching/attenuating element, but if 3 pairs of ribbons are deflected with the same drive voltage, then the switching/attenuating element size is increased by 3×. This absence of boundaries between modulating elements is a key feature of the GLV device. When employed as a spatial light modulator in imaging applications, this seamless characteristic provides a virtual 100% fill-factor in the image.

The GLV array, which Silicon Light Machines has extensively developed over nine years, is an optical MOEMS device built predominantly in a CMOS manufacturing facility. The compatibility between the GLV MOEMS process and CMOS fabrication permits use of highly optimized and tested processes, rapid wafer lot turn-around time and device development, high yield, tight process tolerances, and automated process monitoring.

Today, the GLV technology is successfully used in high-resolution display, digital imaging systems and WDM telecommunications, where its high efficiency, large dynamic range, precise analog attenuation, fast switching speed, high reliability, high yield, and the ability to integrate thousands of channels into a single device are fundamental advantages.

2. GLV MOEMS DEVICE

2.1 GLV device characteristics

Structure:
The GLV device is essentially an addressable dynamic diffraction grating. The cross-sectional diagram of the GLV array is shown in Figure 2.1. The top layer of the ribbons is a light reflecting, as well as an electrically conducting, material. The top layer of the base is a conducting, but not necessarily reflecting, material. The GLV device structure consists of active (electrostatically deflectable) ribbons interlaced with static (undeflectable) ribbons. The active ribbon deflection can be controlled in an analog manner through the applied voltage between the ribbon and base conductor.

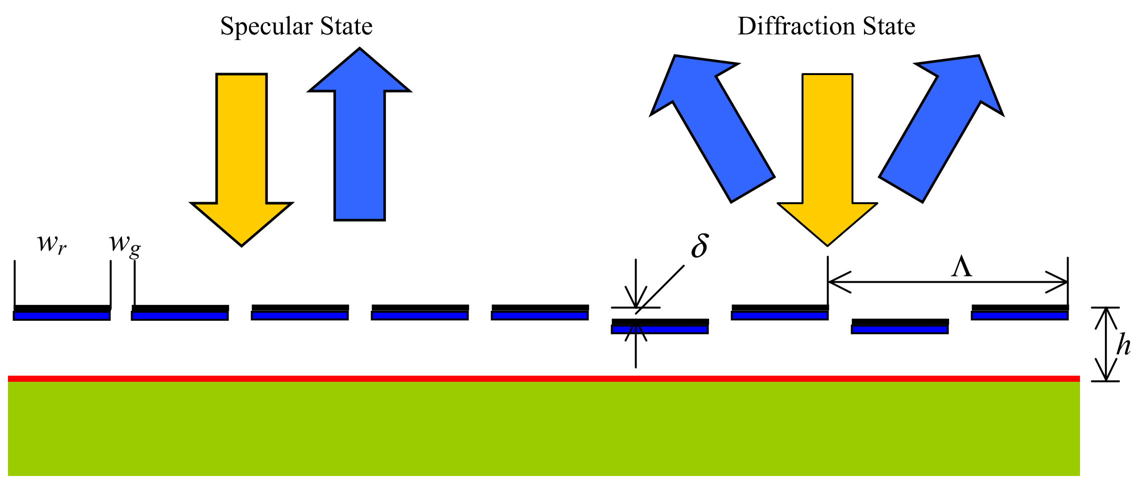


Figure 2.1. Cross-section of the GLV device, w_r is the ribbon width, w_g the inter-ribbon gap width, h the ribbon-to-substrate height, Λ the diffraction period, and δ the ribbon deflection.

Electromechanical property:
The electromechanical behavior of the GLV ribbon can be described by the spring-capacitor model as shown in Figure 2.2. When a voltage is applied, the ribbon is pulled toward the base by Coulomb force $F_{elec} = \beta V^2/(h\text{-}\delta)^2$, where β is a constant that depends on the ribbon area and the effective permitivity. At sufficiently low voltages, the deflection reaches an equilibrium position due to the counteracting Hookes Law force $F_{mech} = k\delta$, where k is the Hooke constant.

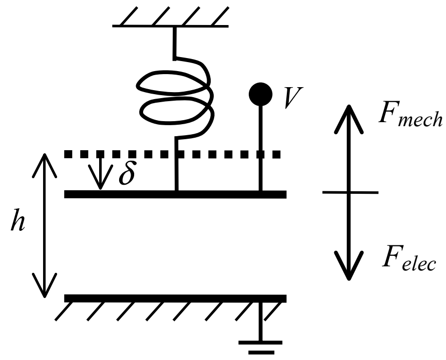


Figure 2.2 Schematic illustration of the forces applied to the GLV ribbons

The equilibrium occurs at:

$$\delta^3 - 2h\delta^2 + h^2\delta - \frac{\beta}{k}V^2 = 0 \cdot \qquad (2.1)$$

This equation does not have a stable solution for $\delta > h/3$, which corresponds to $V > (4kh^3/27\beta)^{1/2} \equiv V_s$. The Hooke force is not strong enough to balance the Coulomb force and the ribbon will snap to the base. In the stable domain, the cubic equation (2.1) can be solved in close-form. However, a simple and more illustrative approximation is

$$\delta(V) = \frac{h}{3}\left[1 - \left(1 - \left(\frac{V}{V_s}\right)^{\omega}\right)^{\frac{2}{3\omega}}\right] \quad . \qquad (2.2)$$

The value $\omega = 1.8$ for the fitting parameter yields a good result.

Diffraction:
For most practical applications, scalar diffraction theory can be used as a good description for the GLV diffraction. The diffraction efficiencies for zeroth and first order light are:

$$\eta_0 = R_r\mu^2 \cos^2\left(\frac{2\pi\delta}{\lambda}\right) + R_g(1-\mu)^2 + 2\sqrt{R_r R_g}\,\mu(1-\mu)\cos\left(\frac{2\pi\delta}{\lambda}\right)\cos\left(\frac{2\pi(\delta - h)}{\lambda}\right) \qquad (2.3a)$$

$$\eta_{\pm 1} = \frac{4}{\pi^2}R_r \sin^2\left(\frac{\mu\pi}{2}\right)\sin^2\left(\frac{2\pi\delta}{\lambda}\right) \qquad (2.3b)$$

In these equations, R_r is the ribbon reflectivity, R_g the gap reflectivity, μ the fill-factor defined as $w_r / (w_r + w_g)$. Maximum diffraction is achieved when the ribbon deflection is $\lambda/4$ (exact for 1st order, approximate for 0th order).

The dominant power exchange is between the 0th and 1st orders. Therefore most applications are either based on 0th order operation (where only the 0th order is transmitted and all the other orders are blocked), or 1st order operation (where either or both the 1st order are transmitted and all the other orders are blocked).

Some general comments regarding the use of zero- or first-order diffracted light (Silicon Light Machines has developed commercial products using the GLV device in both configurations) can be made:

- **Diffraction efficiency**: The 0^{th} order diffraction efficiency is higher than the 1^{st} order diffraction efficiency for fill factor values of $\mu > 0.89$; the situation reverses for $\mu < 0.89$.
- **Contrast**: The 1^{st} order will automatically gives a very high contrast. High 0^{th} order contrast can be achieved by careful choice of GLV parameters and GLV device operation.
- **Optics implementation**: the 1^{st} order beams are diffracted in two different directions and require faster Fourier transform optics compared to the single 0^{th} order beam. In cases where contrast outweighs optical efficiency, transmitting only one 1^{st} order beam may be a solution.

The two results expressed in equations (2.2) and (2.3) describe the diffraction efficiency versus voltage behavior, i.e. $\eta(V)$, often expressed by its non-normalized version as the Intensity-Voltage curve. The I-V curve is an important measure of the accuracy of the analog light modulation. In digital imaging, digital information is converted into analog voltage by digital-to-analog converter (DAC) electronics (usually 8-10 bits).

2.2 GLV device fabrication
The ribbons are 200-300 nm in thickness and under high tension of ~800 Mpa so that they remain taut when not actuated. The top layer of the ribbon is aluminum that serves as both the reflective layer and the top electrode for electrostatic actuation. The sub-layers of the ribbon are a carefully designed sandwich of stoichiometric Si_3N_4 and SiO_2 films that provides the spring-like restoration force that counter-balances the electrostatic actuation force, and which provides stiffness and stress balance so the ribbon remains flat across its width. Ribbons are 100-1000µm long, 1-10µm wide, and closely spaced (the gap between ribbons is around 0.5µm).

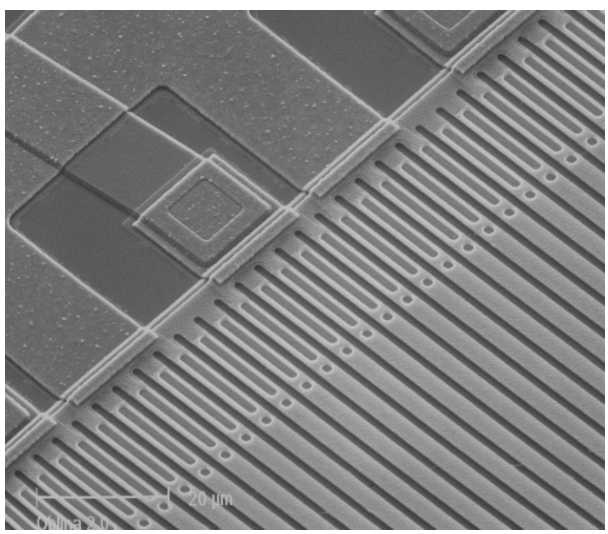


Figure 2.3: SEM photograph of GLV ribbons.

To build the GLV device, the ribbon layers are deposited on a sacrificial layer, which is isotropically etched using a proprietary dry xenon-difluoride to remove the sacrificial layer material from underneath the ribbon layers to release the ribbons and form the air gap. The thickness of the sacrificial layer must be carefully optimized for operation in the spectral region of interest. Below the sacrificial layer is an etch stop layer that protects the underlying bottom electrode during the release process.

To form a complete GLV device, the ribbons are replicated several thousand times to form a 1-dimensional array of diffracting elements, as shown in Fig. 2.3. Again, the compatibility with CMOS processing makes this an easy task. A key feature of the GLV array is that the individual diffraction elements are seamless in that there are no physical boundaries, or dark spaces between elements.

2.3 GLV device measured performance

The performance of the GLV device as a spatial light modulator has been extensively characterized against a number of standard performance metrics: optical attenuation resolution versus applied voltage (I-V curve), device lifetime (in total ribbon cycles), and attenuation stability over long open-loop operation. The data plots below illustrate the capabilities of the GLV device in all these categories. However, it should be clearly noted that the exact device dimensions and configuration used when gathering these data are different and performance trade-offs must be made when designing a GLV device to optimize a certain performance parameter for a specific application.

Intensity-Voltage curve

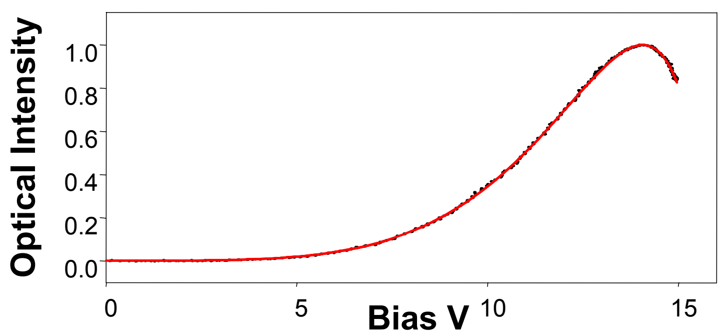


Figure 2.4: Intensity-Voltage in the 1st order operation.

The experimental Intensity-Voltage curve in the 1st order operation is shown in Figure 2.4.

Reliability

The GLV device has been tested for reliability as well as for its stability. Figure 2.5 below is test data taken on the resonant mechanical frequency of a set of GLV ribbons after they were deflected more than 5 x 10^{12} cycles.

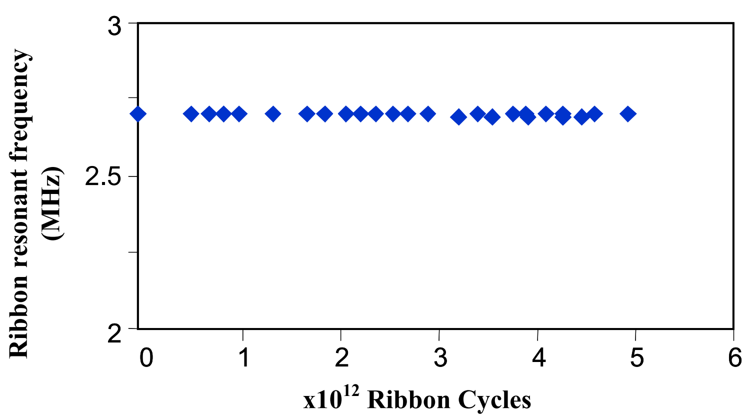


Figure 2.5: Data on the GLV ribbon reliability under prolonged actuation.

From the graph it is apparent that the resonant frequency is unchanged, indicating that the mechanical integrity of the ribbon structures has not been altered in any way, even after lengthy operation of the device.

Detailed stability tests on the GLV device have also been conducted. A GLV array was configured to impart 16 dB of attenuation on to a laser beam in 1550 nm spectral region. The net output light intensity (in zero order) was monitored and the GLV ribbons were deflected sufficiently to produce the desired attenuation of 16 dB. The output light level was then examined periodically over a period of approximately 16 months to detect drifts in the GLV ribbons from their set deflection values. The data collection over this time is shown in Figure 2.6 below.

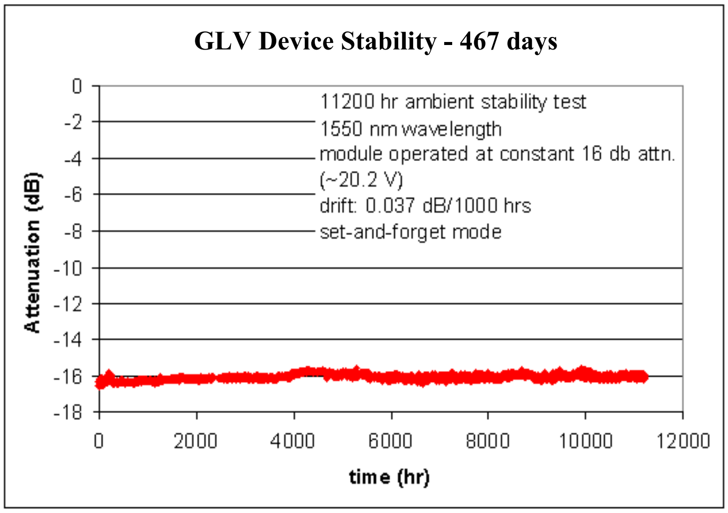


Figure 2.6: Attenuation stability of the GLV pixel.

The average drift rate was determined to be approximately 0.04 dB per 1000 hours of operation. This translates to a total inferred drift in the ribbon deflection of less than 0.5 nm over 16 months of continuous open-loop operation.

3. OPTICAL WRITE ENGINE

The optical write engine consists of the illumination subsytem, the GLV module and associated drive electronics, and the imaging subsystem. A GLV-based optical engine is a system that contains the three subsystems, where an input laser beam is transformed into a spatio-temporal image bearing beam at the output port. The output is usually imaged to the target of a particular application, such as a screen in display, an aluminum sheet in offset printing, or a silicon wafer in maskless lithography.

3.1 Illumination optics

The illumination optics converts a Gaussian-profile laser beam into a line with flat-top intensity profile (along the long dimension of the GLV array), and a footprint that is compatible with the GLV device specification. The length of the footprint along the GLV device is such that the length of the flat-top portion is equal to the GLV device length. To ensure good light modulation, the width of the footprint must cover only the most deflected portion of the ribbon (around the ribbon center). For example, a 25 mm long GLV device with 200 µm ribbon requires a 25 mm flat-top portion and a few tens of micron footprint.

The Gaussian-to-flat-top conversion is accomplished by employing over-corrected spherical aberration from a cylindrical aspheric lens that has a hyperbolic profile, sometimes called the Powell lens. A Powell lens is designed for a Gaussian beam with a specified e^{-2} diameter. Two orthogonal cylindrical lenses follow the Powell lens, one for collimation that matches the GLV device length, the other for focusing the beam to meet the required illumination footprint width (few tens of microns in the above example).

3.2 GLV module
The GLV module consists of the GLV die (hermitically sealed by an anti-reflection coated cover glass), driver chips, immediate electronics and input-output interface electronics. Figure 3.1 shows one example of a GLV module that is currently in production.

Figure 3.1: A GLV module, including drive electronics and data interface

3.3 Fourier filter optics
The function of the post-GLV device optics is to pass the chosen diffraction order by Fourier filtering, and then to image the amplitude information at the image plane (final or intermediate) with suitable magnification.

The GLV device can be viewed as a special type of phase modulator. If all diffraction orders are collected, no contrast (i.e. no intensity modulation) will be observed at the image plane. The amplitude information carried by the orders, 0^{th} and 1^{st} orders to a large degree, are complementary, hence no contrast will result. The location where the orders are optimally separated is at the Fourier transform plane. Therefore, it is the best place to put the spatial filter (this Fourier filter is analogous to the Schlieren filter in phase contrast imaging). See Figure 3.2.

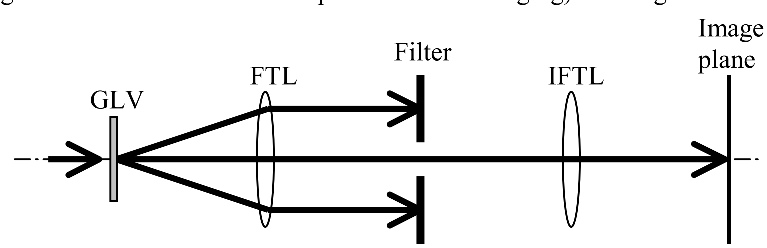


Figure 3.2(a) Imaging Optics 0^{th} order operation

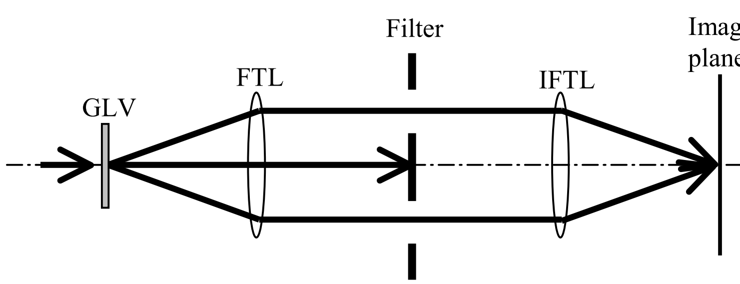


Figure 3.2(b) Imaging Optics 1^{st} order operation

In Figure 3.2, FTL is the Fourier transform lens and IFTL the inverse Fourier transform lens. The FTL and the IFTL together form an imaging optical system which image the GLV device to the image plane.

3.4 The optical write engine
A complete assembly of the optical write engine is displayed in Figure. 3.3.

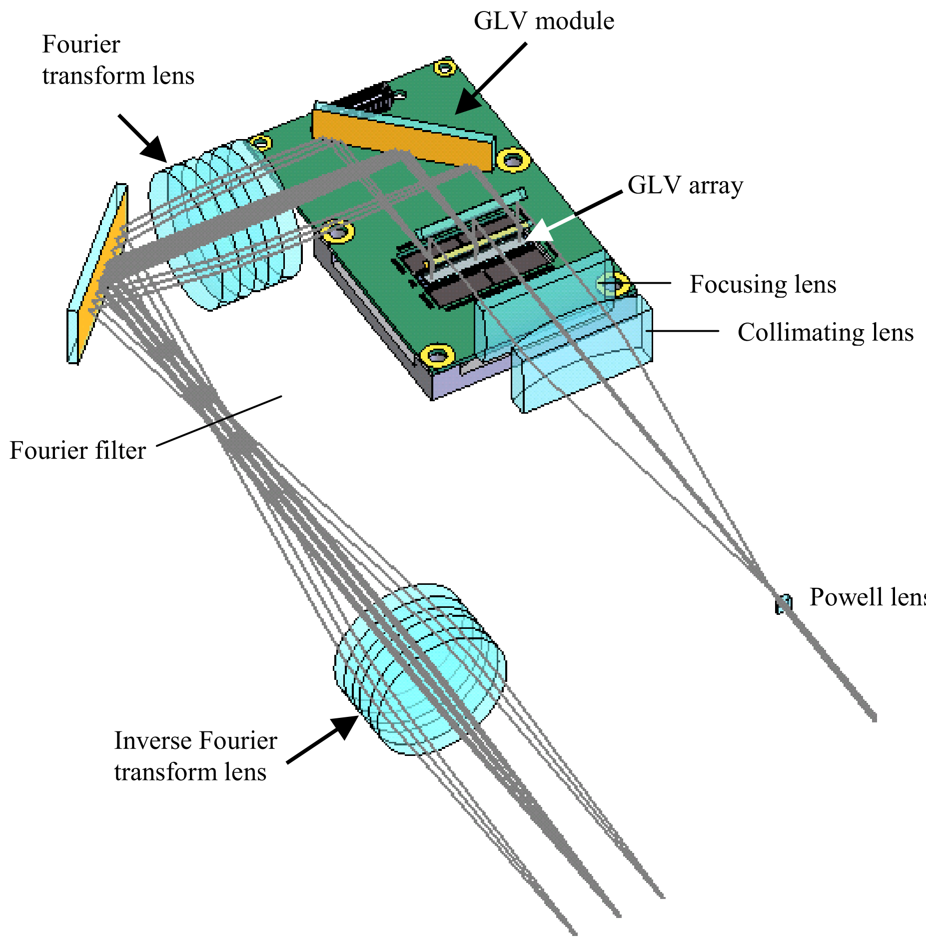


Figure 3.3: A GLV optical write engine.

3.5 Performance of the optical write engine

Efficiency
The typical optical efficiency breakdown is as follows:
- Illumination optics: is around 70% (most of the loss is from the geometric overfill and uniformity calibration).
- GLV device: 65-70%, depending on detail structures and whether it is 0^{th} or 1^{st} order operation
- Imaging optics: 85%

Therefore the optical throughput of the write engine typically ranges from 38% to 42%.

Contrast

Contrast is established with the filter at the Fourier transform plane. It depends on the spatial frequency band that the orders carry relative to the order spacing, as illustrated in Figure 3.4 below.

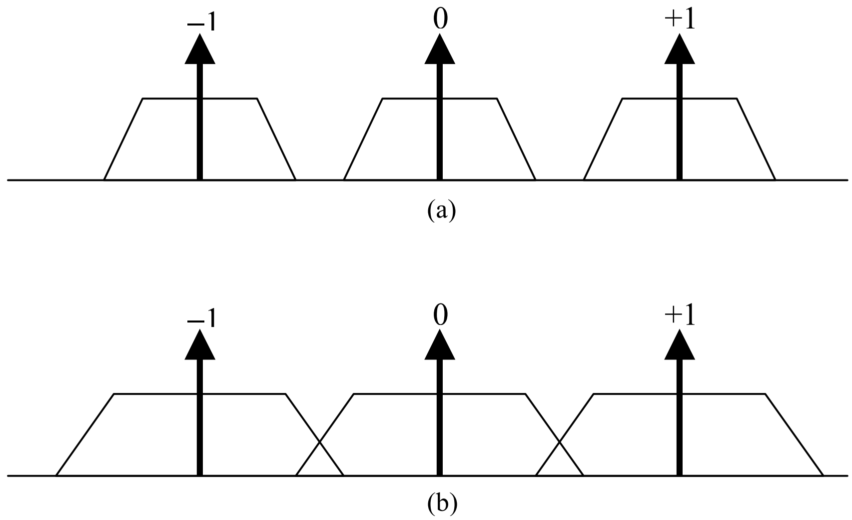


Figure 3.4: Spatial frequency spectra at the Fourier transform plane with (a) a good and (b) poor discriminations.

It is obvious that the spatial frequency spectrum in Figure 3.4(a) permits good discrimination, hence the contrast. In the undesirable situation of figure 3.4(b), either the information is reduced (by some truncation of the band) or the contrast is compromised. In general, the latter case can be avoided simply by assigning a sufficient number of ribbon-pairs (periods) per pixel. In practice, three ribbon-pairs per pixel is usually enough as shown in figure 3.5 at 355nm wavelength (the actual 0^{th} order device contrast is higher than that shown in Figure 3.5(a); this data includes the non-negligible Fresnel reflection from the cover glass).

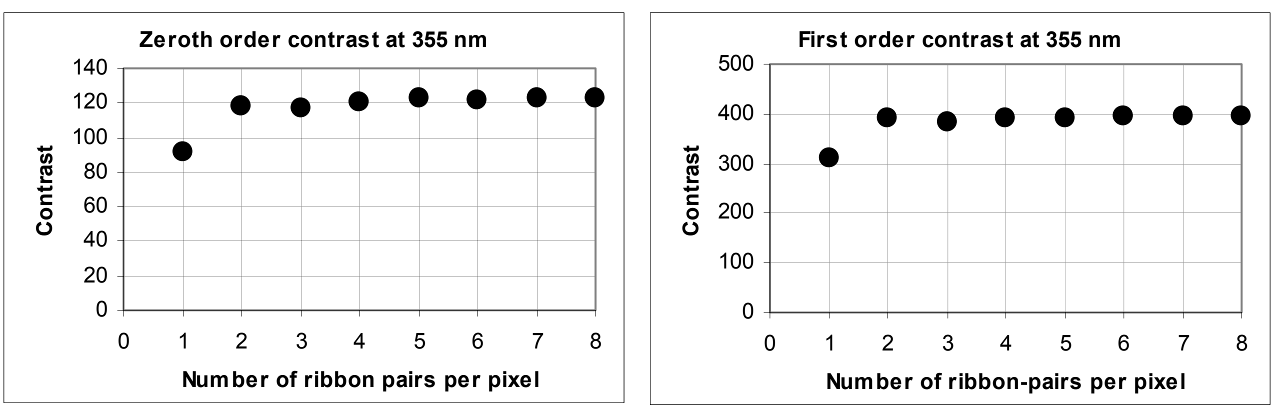


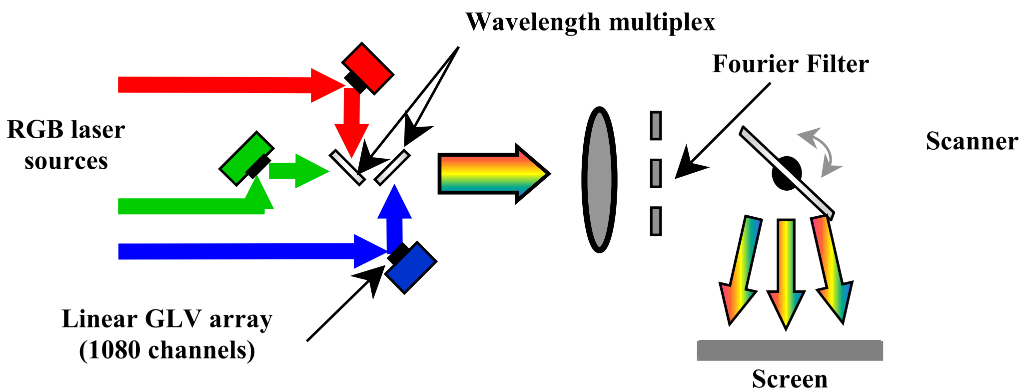
Figure 3.5: The 0^{th} and 1^{st} order contrast dependency on the number of ribbon pairs per pixel, 355 nm illumination. In general, the contrast can be >100:1 for 0^{th} order operation, and >300:1 for 1^{st} order operation.

4. APPLICATIONS

4.1 Display

The GLV technology has been applied to wide range of products, from laser-based HDTV sets to computer-to-plate offset printing presses to DWDM components used for wavelength management. Applications of the GLV device in maskless photolithography have also been extensively investigated.

Prototype HDTV front-projection sets[2] have been demonstrated using a 1080 pixel GLV array in a scanned architecture, as shown in Figure 4.1 below.



Pixels per Image: 2 x 10^6
Data flow ~ 800Mbit/sec (per GLV)

Figure 4.1 Schematic layout of a GLV-based HDTV projector

Commercialization of this display application of the GLV device has been exclusively licensed to SONY Corporation. As a spatial light modulator for display systems the GLV device has demonstrated high contrast ratios (>3,000:1) at visible wavelengths and very rapid pixel modulation rates (300 kHz to 1 MHz). The optical properties of the GLV device make it best suited to the use of a laser light source, as the etendue, or optical invariant, of a GLV pixel is only ~ $E_{pixel} = 5.36 \times 10^{-6}$ mm^2·srad, while the pixel etendue for the DMD MOEMS spatial light modulator from Texas Instruments is $E_{pixel} = 15 \times 10^{-6}$ mm^2·srad. This etendue advantage allows the DMD to be efficiently coupled short-arc lamps and other incoherent light sources for digital display and imaging products.

4.2 Computer to plate printing

Another imaging application of the GLV technology is in computer-to-plate (CTP) printing[3]. The GLV device serves as a high-speed, high-resolution linear spatial light modulator for a high-power CW diode laser bar source that is imaged on to offset plates, as shown below:

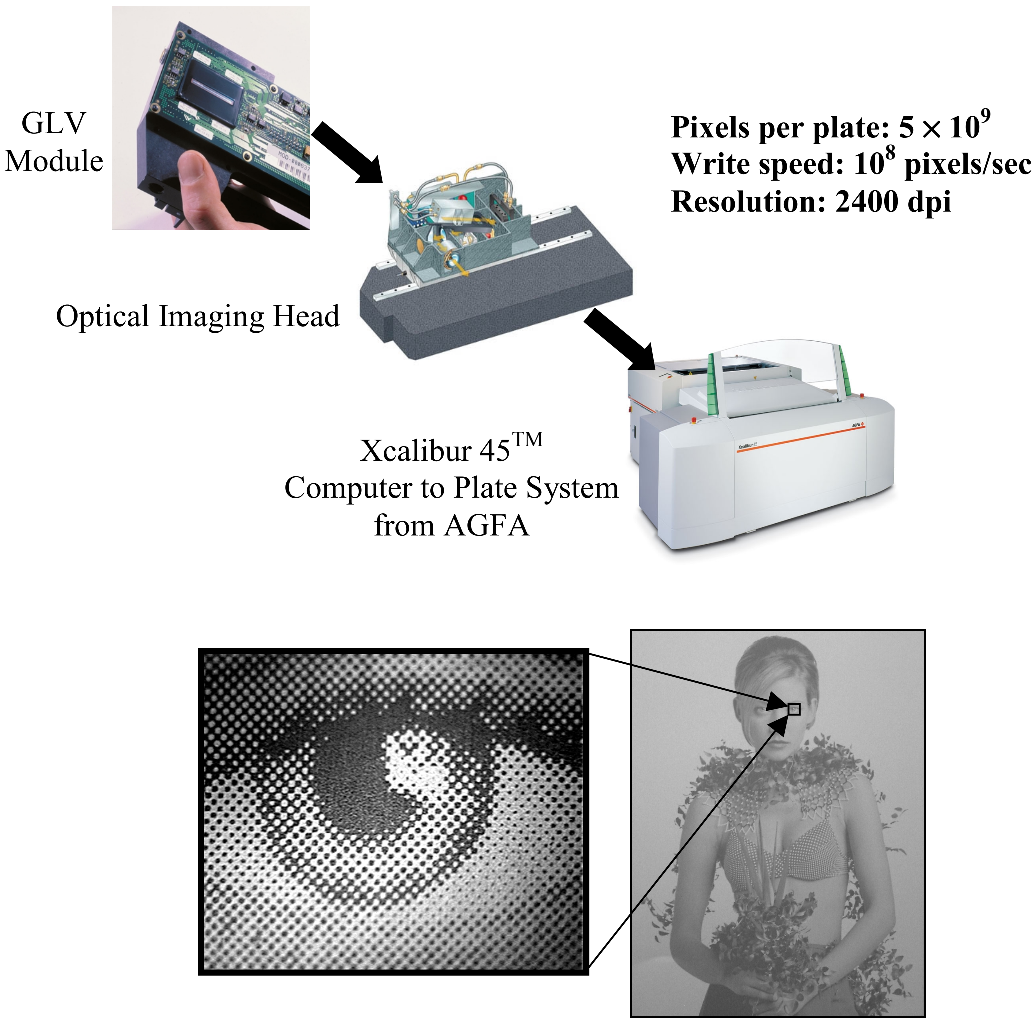


Figure 4.2 Use of the GLV technology in computer-to-plate thermal offset printing

The performance of the GLV module in this product is impressive: Laser powers > 60 Watts are processed at irradiance levels at the GLV array ranging from 1 to 10 kW/cm^2. The GLV device can impart attenuation levels over 8 bits of gray scale at line rates beyond 300 kHz to this high-power laser source, while maintaining a specified product lifetime greater than 10,000 hours. Figure 4.2 below presents an image printed at 2400 dpi using the GLV device on a CTP printing tool developed by Agfa Corporation.

4.3 Direct-write UV lithography
Digital imaging in the 190nm to 450nm wavelength range offers numerous potential applications: large area LCD and flat-panel display patterning (low resolution), maskless lithography for MEMS (medium resolution), and maskless lithography for IC chips (high resolution), to name just a few.

Figure 4.3 shows some patterns written on a silicon wafer coated with i-line photoresist, using a tripled Nd: YVO_4 laser at 355nm wavelength.

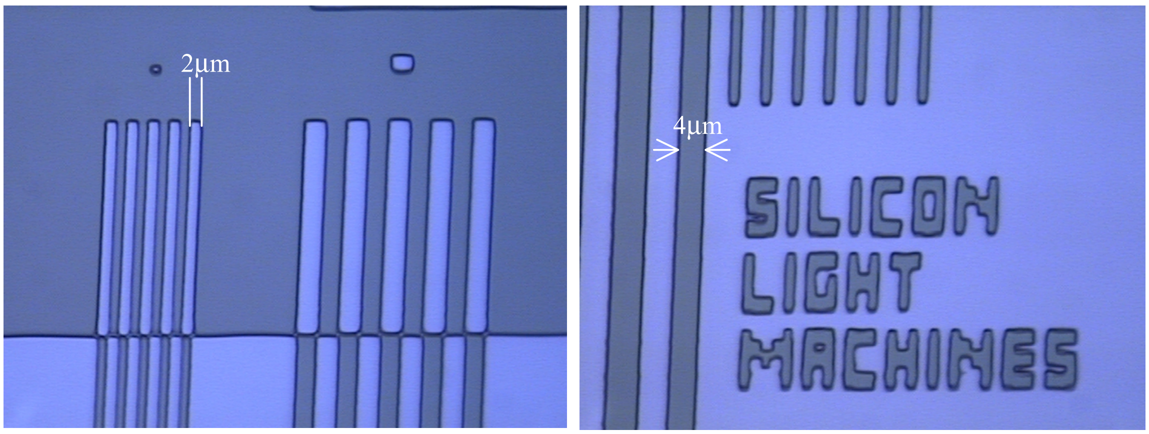


Figure 4.3

The unique combination of very high modulation speed, inherent gray-scale attenuation, and high-contrast make the GLV device a key enabling spatial light modulator technology for numerous emerging products in digital displays and imaging.

5. FUTURE DIRECTIONS

5.1 Two-dimensional GLV arrays
Compared to other spatial light modulator technologies, the fast speed and analog (or gray level) capabilities of the GLV device are two of its most important advantages (for certain applications, high optical power handling is another). Recently, there has been a number of emerging applications in which the extension of GLV device structure to a 2-D array may offer an attractive solution. However, the GLV ribbon structure prevents deployment in a 2-D dense-pixel array. A 2-D sparse pixel GLV device is perfectly suitable for maskless lithography concept initially proposed by Ball Semiconductor, for example[4]. The development of die with two-dimensional arrays of GLV pixels is under investigation currently by Silicon Light Machines.

5.2 GLV arrays with integrated drive electronics
Applications for the GLV technology that require large numbers of pixels (i.e. more than a few thousand) lead inevitably toward MOEMS die architectures that include integrated drive electronics. As the GLV device and its associated 8-10 bit drive electronics are both die fabricated on the same CMOS process line, the integration of the two is straightforward. Silicon Light Machines is actively investigating integrated MOEMS die for several future products.

6. SUMMARY

This paper describes in some detail the numerous applications of the unique GLV MOEMS technology in digital displays and imaging. The wide range of different commercial products in which the GLV device has been deployed, such as HDTV, CTP printing presses, and DWDM telecommunication components, illustrate the strength and versatility of diffractive MOEMS technology.

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