# Silicon Light Machines™ – Grating Light Valve™ Technology Brief

*Breakthrough MEMS Component Technology for Optical Networks*

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## Introduction

Silicon Light Machines was founded in 1994 to develop and commercialize a range of products based on the Grating Light Valve™ (GLV™) technology. The GLV device is a type of optical micro-electromechanical system, or MEMS; essentially a movable, light-reflecting surface created directly on a silicon wafer, utilizing standard semiconductor processes and equipment.

The original GLV device concepts were developed at Stanford University. In addition to a license on the original Stanford work, Silicon Light Machines has over 100 patents issued or in process covering many aspects of GLV device design and fabrication.

The company—now a wholly owned subsidiary of Cypress Semiconductor Corp.—has combined expertise in MEMS process technology, MEMS design and test, optics design and optical network engineering. Currently, Silicon Light Machines' customers are using GLV technology in optical attenuators and switches, direct-to-plate printers, HDTV monitors, electronic cinema projectors and commercial flight simulator displays.

Silicon Light Machines is leveraging its successes to develop a portfolio of products based on current GLV structures and future derivatives, to serve the needs of its customers in the rapidly emerging optical communications network markets.

## Overview – MEMS Structures for Optical Communications Systems

There are several ways to switch laser light, including polarization, reflection and diffraction (interference). In optical communications, the two techniques generally used are reflection and diffraction. Most optical MEMS devices are derivatives of moving mirrors and operate as tiltable reflective surfaces. GLV devices are unique in that they operate as mirrors in the "OFF" state, and as diffraction gratings in the "ON" state — with the application of control voltages (see Figure 1).

### Tilting Mirror MEMS

Traditional optical MEMS structures are true micro-machines that incorporate actual mechanical components such as mirrors mounted on some form of a mechanical bearing device. Source light is reflected as a mirror sweeps across an arc, sending light from one location to another.

In many tilting mirror designs, the MEMS device is etched out of a silicon substrate, with the control surface coated with a reflective material such as gold or aluminum, leaving a mirror on a bearing surface. In order to allow mechanical clearance to sweep a mirror of adequate size over a suitable range of angles, the mirror surface and supporting hinges or gimbals often must be "lifted up" off the surface of the silicon, requiring complex self-assembly techniques. The movement and positioning of the mirror may require precise control electronics and accurate feedback mechanisms. In operation, this type of device will "sweep" light at constant amplitude from the source to the destination fiber. In other words, the light amplitude is constant; the output angle is variable.

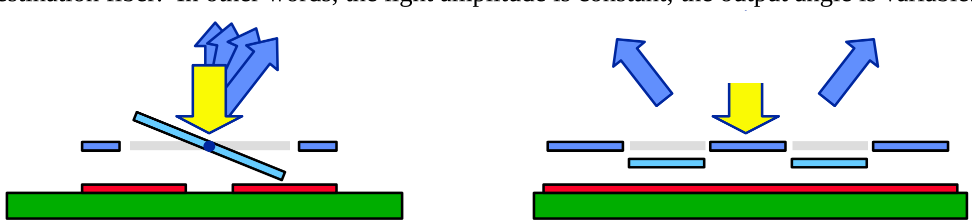

**Figure 1.** **Tilting Mirror Optical MEMS** **GLV Diffraction Grating MEMS**

**Diffraction Grating MEMS**

Silicon Light Machines has pioneered another major type of optical MEMS based on an addressable diffraction grating. Silicon Light Machines' Grating Light Valve (GLV) devices utilize the principle of diffraction to switch, attenuate and modulate light. A GLV device is a dynamic diffraction grating that can serve as a simple mirror in the static state, or a variable grating in the dynamic state. This unique approach offers significant functional advantages in terms of speed, accuracy, reliability and ease of manufacturing over the common "tilting mirror" MEMS structures.

## GLV Device Advantages

When compared with more conventional optical MEMS technologies, Silicon Light Machines' GLV technology offers the following advantages:

1. Significantly faster operating speeds
2. High optical efficiency (low insertion loss)
3. Continuously variable attenuation that is highly accurate and repeatable
4. Optical angular repeatability that is permanently set with photolithographic precision
5. No contact surfaces — high reliability and stability
6. Scalability to very large numbers of separately addressed channels
7. Ease of manufacturing
8. Ease of integration with CMOS logic

## GLV Device Fundamentals

Each GLV device element (the minimum addressable optical switch element) is a variable diffraction grating, formed of moving parts on the surface of a silicon chip. Each GLV element consists of (typically) six dual-supported parallel ribbons formed of silicon nitride ($Si_3N_4$) and coated with a reflective top layer. This top layer is used as both an optical element and an electrical conductor. The surface below the ribbons operates as a common electrode, as shown in Figure 2. Ref [1-4]

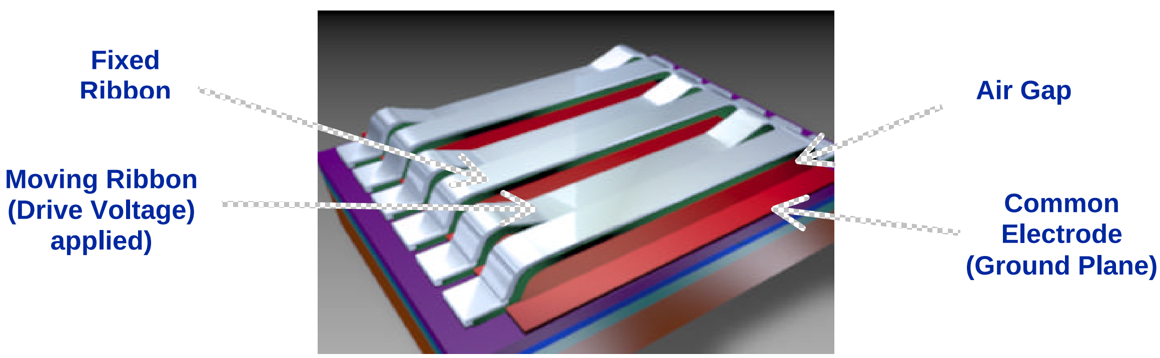


**Figure 2. Basic GLV Structure**

An element is set to the fully reflecting state when all element ribbons form a flat reflective plane. An element is set to the diffracting state by electrostatically deflecting alternate ribbons to produce a square-well diffraction grating. GLV elements can be operated in either a digital mode (with alternate ribbons either not deflected or deflected to precisely $\lambda/4$) or a continuously variable analog mode (with alternate ribbons deflecting to positions between zero and $\lambda/4$), as shown in Figure 3.

 

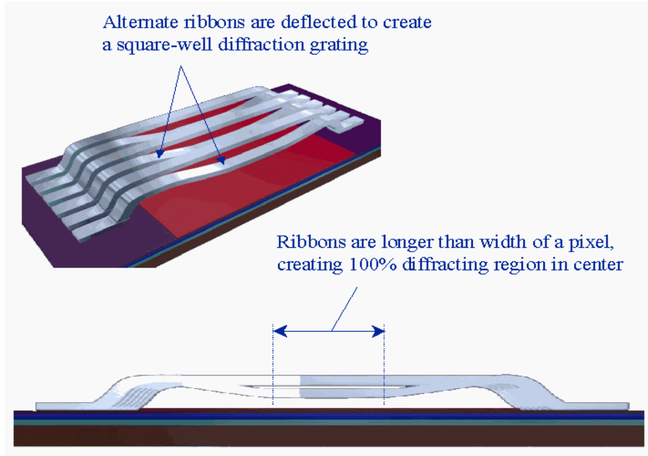


**Figure 3. GLV element with alternate reflecting ribbons electrostatically deflected to produce a square-well diffraction grating (vertical deflection greatly exaggerated)**

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, as the space between ribbons is quite small relative to the width of the ribbons themselves. Second, any potentially diffracting features of the intended reflective state (such as the ribbon gaps themselves) are expressly created at twice the spatial frequency of the square-well diffraction grating when the ribbons are deflected. Thus any undesirable diffraction occurs at larger angles, and does not affect contrast in the first-order diffraction lobes.

### High Speed Operation

The on/off switching speed (or the time required to switch between any other two arbitrary intermediate values) of the GLV device can be several orders of magnitude faster than competing technologies (see Figure 4). Specific GLV devices capable of switching speeds as fast as 20 nanoseconds have been fabricated.

The fundamental switching time of the GLV element is related to the resonant mechanical frequency of the ribbon design, determined by such factors as ribbon length, ribbon width, ribbon tension, ribbon mass, 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 through the proper design of electronic drive circuitry and by "tuning" the GLV device and its ambient atmosphere so that it is critically damped at its natural frequency. Extensive characterization and testing of such parameters allow Silicon Light Machines engineers to optimize the switching characteristics for a particular application. Given all of these trade-offs and design latitudes, a wide design space can be covered with the GLV technology. Depending, then, on the specific design trade-offs involved, for most optical communications applications, GLV devices can switch with sub-microsecond speeds.

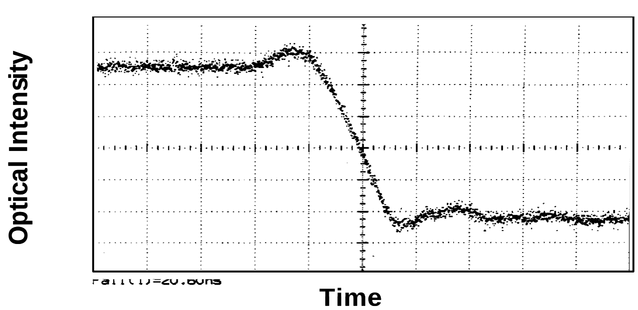


**Figure 4. Switching Speed of Optimized GLV Device**
**(X-Axis time@ 5 nsec/division, Y-Axis Volts@ l volt/division)**

**Optical Efficiency**

The optical efficiency of the GLV device depends on three main factors: 1) the diffraction efficiency, 2) the aperture ratio (the ratio of ribbon width to ribbon gap) and 3) the reflectivity of the top layer material chosen. In an ideal square-well diffraction grating, 81% of the diffracted light energy is directed into the +/- $1^{st}$ orders. 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. Practical designs have been realized with an effective fill factor efficiency of about 95%. Reflectivity of the top layer depends on the choice of material selected. While other materials can be selected (such as gold), aluminum alloys typically used in semiconductor processes allow cost-effective manufacture and are greater than 90% reflective over most of the wavelengths used for optical communications and imaging applications. Device efficiency, then, is the product of diffraction efficiency (81%); fill factor efficiency (typically >95%), and aluminum reflectivity (typically >91%). Overall, the device efficiency is about 70%, corresponding to an insertion loss of about 1.5dB.

**High Attenuation Accuracy**

The GLV device performs smoothly and monotonically for well over three decades of intensity (see Figure 5). The response of the GLV device to a given input voltage has been painstakingly modeled, and is well understood through extensive empirical data as well. Using 8-bit drivers, the GLV ribbons can be positioned with attenuation accuracy greater than 0.07dB. Use of higher resolution drivers (such as 10-bit) can allow for even greater attenuation accuracy in cases where this is required.

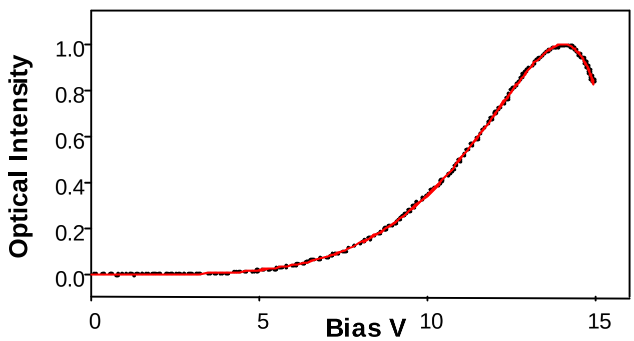


**Figure 5. Relative Optical Attenuation Levels for Given Voltage Input**

**High Optical Precision**

When a voltage is applied to alternate ribbons, the GLV device is set to a diffraction state. The source light is then diffracted at set angles, as illustrated in Figure 1. These diffraction angles are fixed with photolithographic accuracy when the GLV device is manufactured. Therefore, very precise light placement is achieved *without* the need for complex control electronics. This feature of the GLV device allows for significantly smaller and less expensive packaging and lower power requirements for optical components and subsystems.

**High Reliability and Stability**

Another requirement for the optical communications market is high component reliability. The simple mechanical and electrical design of the GLV technology is intrinsically reliable. The ribbons (the only moving mechanical elements) are made of silicon nitride, a hard, amorphous, ceramic material grown by a stable thermal deposition process (LPCVD). The reflective (aluminum) top layer has minimal influence on ribbon mechanics. When fully actuated, the ribbons operate at less than 10% of $Si_3N_4$'s tensile breaking stress. Moreover, the ribbons operate in a non-contact mode with relatively small ribbon deflections. For purpose of illustration, if a GLV element were scaled up such that the ribbon length was 10 meters, the depth of deflection for a fully switched ribbon would be only 6.5 millimeters. GLV ribbons never experience contact, so there are none of the wear issues sometimes associated with other MEMS processes and devices. Silicon Light Machines has developed a unique method for hermetically sealing the active ribbons under an optical glass lid which protects the delicate ribbon structures while still at the wafer level, thus eliminating contamination during subsequent processing and packaging.

Because of the "mission critical" nature of optical communications systems, Silicon Light Machines has conducted a comprehensive, statistically based testing program to analyze the impacts of various types of component stress (e.g., thermal, mechanical, advanced cycles, high optical power) that most affect long-term GLV reliability, and to demonstrate reliable long-term GLV performance. The long-term stability of ribbon tension is crucial to the proper operation of GLV devices. For reliability testing, it is thus important to monitor even small changes in ribbon tension. The natural resonant response for an individual ribbon—a characteristic damped oscillation when excited by a square-wave drive voltage—is ideally suited for this task. Natural resonance is a sensitive indicator of the ribbon's mechanical properties, and can be measured with automatic test equipment to better than one part in 2000. Thus, monitoring the ribbon natural frequency before and after testing provides a very sensitive and accurate gauge to measure any change in the ribbon tension resulting from the applied stress. Individual GLV devices have undergone greater than 6 x $10^{12}$ switching cycles, making the GLV technology one of the most-tested light modulator technologies (see Figure 6). Ref [2]

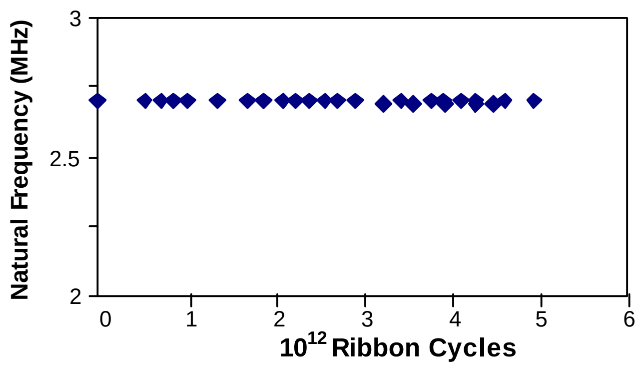


**Figure 6. Data for GLV Device Life Cycle Testing**

Another unique feature of the GLV device is its ability to withstand extremely high optical power densities. As previously mentioned, the GLV device is composed of simple, stable materials. The surrounding structures and conductors are silicon, polysilicon, and silicon dioxide. This material set is very robust by design. And, unlike many tilting mirror MEMS designs, there is no logic or control electronics close enough to the active ribbon area to be affected by either (laser) source heat or photonic effects of scattered light.

As a practical example, in commercial direct-to-plate applications, the GLV devices are routinely tested to optical power levels measured in 10s of $kW/cm^{2,}$ with no degradation in behavior. These numbers contrast with other modulator technologies that are typically limited to power thresholds of 1 $W/cm^2$ or less — several orders of magnitude lower than the GLV devices. As Dense Wavelength Division Multiplexing (DWDM) systems move from 8 to 40 to hundreds of wavelengths, power density will become a serious component design issue. Unlike many competing technologies, the GLV device is meeting the challenge of high-density power today.

**Scalability**

The fundamental diffraction grating pattern used to form a single GLV switching element can be extended by adding multiple elements placed side by side. When this is done, there are absolutely no gaps between adjacent elements. If all elements in a multi-element array are set to the same value, the output of a uniformly illuminated linear array is a completely smooth and flat line. Alternatively, each element can be finely tuned to continuously variable attenuation levels, so a linear GLV array can have a unique capability for analog gain shaping.

**Ease of Manufacturing**

Another important attribute of the GLV device for optical communications applications is its ease of manufacturing (including flexibility of design parameters and potential for low cost). Silicon Light Machines currently manufactures GLV devices at the Cypress Semiconductor foundry in Round Rock, Texas, using entirely conventional CMOS materials and process steps, and only seven photolithographic masks.

**Ease of Integration with CMOS logic**

Due to the intrinsic simplicity of the GLV device and the choice of materials and processes used by Silicon Light Machines, a GLV MEMS device can be integrated with standard CMOS logic circuitry to form a monolithic MEMS/logic component. This capability enables faster feedback response times, lower component costs at volume, higher component reliability, and simpler packaging.

In summary, the fundamental GLV technology surpasses most other light-modulation technologies in terms of fundamental benchmarking parameters such as switching time, efficiency, accuracy, contrast, and optical power-handling capability. The fundamental design and material set creates a stable and reliable structure. GLV devices are highly scaleable and can be integrated with standard CMOS devices and manufactured on standard CMOS fabs.

## GLV Device Applications

**High-Speed Optical Attenuation**

Due to its continuously variable attenuation, high speed and accuracy, the GLV technology is particularly well suited for application as a variable optical attenuator (VOA) or dynamic gain equalizer (DGE) as used in modern optical communication networks.

In current multichannel or multiband gain equalizers, each channel or band may require a separate VOA device. Multiple VOA devices can be replaced by one GLV device array, saving cost, space and power needed for the gain equalization modules (see Figure 7).

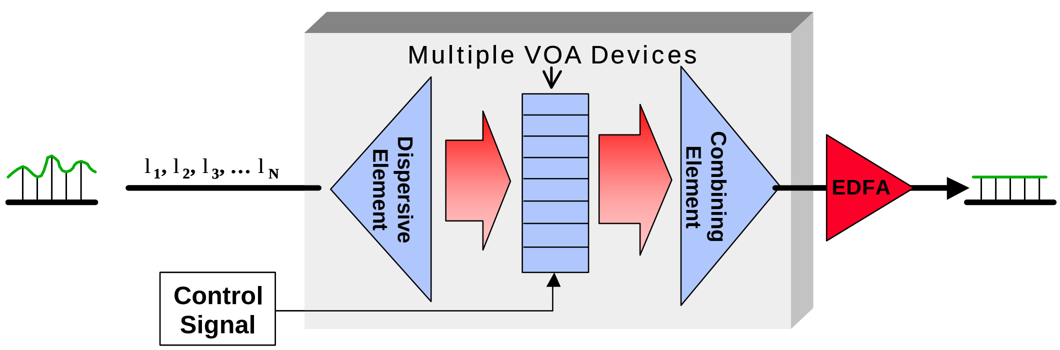


**Figure 7. Typical gain equalizer module requiring multiple VOA devices, one per channel**

Because of the ability to easily gang multiple GLV devices together, it is possible to create a linear array of 2, 10, 100, or over 1,000 GLV device elements.In fact, linear GLV arrays are being used as multi-channel variable optical attenuators for print systems requiring 1080 individually switchable optical elements. Such an array, in module form, is shown in Figure 8. The linear GLV array pictured is surrounded by four custom driver chips (each with 272 output stages) and assembled into a highly manufacturable multi-chip module.

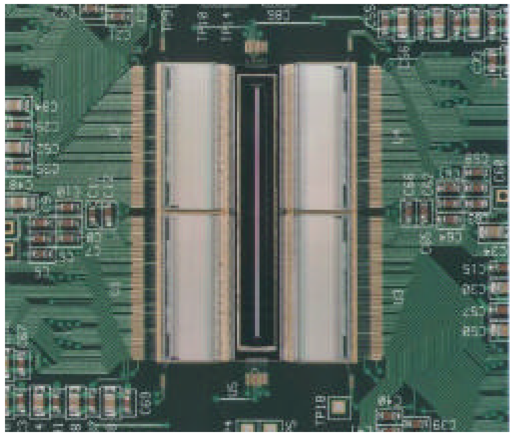

**Figure 8. Multi-chip module consisting of four custom driver dies and a 1,080 element linear GLV array.**

As an application example to illustrate the speed of these devices, three linear GLV arrays of 1,080 variable optical attenuator elements, as described above, have been utilized to create a column of visible light (combined Red-Green-Blue) for an HDTV projector (see Figure 9). The visible light column is scanned at the video refresh rate to paint a full HDTV image (1088x 1920 elements). With the module operating all 1,088 channels at 8 bits at a line rate of 250 kHz, it is capable of processing video data at well over 2 Gbits/sec! Ref [3]

**Figure 9. An HDTV–resolution projector utilizing three GLV device optical attenuator modules**

Additionally, GLV technology is fast enough to be capable of modulating a low bandwidth signal (typically 100KHz to 1MHz) on top of a DWDM wavelength. This is useful for adding telemetry or control signals onto an existing wavelength in an optical system. Using existing wavelengths saves the cost of provisioning an additional DWDM channel or frees up a currently used control channel to transmit additional customer data.

**Optical switches**

Current optical communications networks typically utilize many small optical switches in 1 x 2 and 2 x 2 configurations. These switches are often used to connect redundant equipment and optical fibers in the event of a system failure. These simple switches are typically low cost, minimal loss devices. In the case of SONET type telephony networks, they only need to switch fast enough to allow for the required 50-millisecond failure recovery in the infrequent event of a component or fiber failure.

With the dawn of more purely optical networks, many industry observers have posited the advantages of much faster and more frequent set-up and tear-down of optical routing paths. Simple SONET rings are being transformed into mesh topologies. Data paths are added and dropped daily, hourly, or faster. Individual subscribers may ultimately be assigned bandwidth on demand, requiring fast reconfiguarable networks. Some are proposing routing of optical paths even at the burst or packet rate. These new networks will require switch components having significantly higher speed. Duty cycles will be greater; hence reliability demands are even more severe. And because these new all-optical network topologies require many more optical switch components, cost tolerance will be lower. At this point, there are few technologies that can match the promise of speed, reliability, and cost of a GLV-based switch.

## Summary

The Silicon Light Machines' Grating Light Valve technology is a proven means to switch, modulate, and attenuate light. Its unique combination of speed, accuracy, reliability, and manufacturability has been field-proven in demanding applications in the simulation, display and direct-to-print markets. Silicon Light Machines is leveraging its unparalleled experience and expertise in optical MEMS to create optical communications products for large telecommunications system developers and subsystem OEMs.

## References


**[1] D.T. Amm and Robert W. Corrigan, "Optical Performance of the Grating Light Valve Technology," Photonics West-Electronics Imaging '99, Projection Display V, January 1999**

**[2] R. W. Corrigan, D.T. Amm, and C.S. Gudeman, "Grating Light Valve ä Technology for Projection Displays," International Display Workshop, Kobe, Japan, December 1998.**

**[3] D. T. Amm and R. W. Corrigan, "Grating Light Valve ä Technology," Society for Information Display Symposium, Anaheim, CA, May 1998.**

**[4] D.T. Amm, Report for the DARPA MEMS Semi-Annual Meeting, Contract #DABT63-95-C-0062, Princeton, New Jersey, July 1997.**


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