Spatial Light Modulators

A Spatial Light Modulator (SLM) is an electrically programmable device that modulates light according to a fixed spatial (pixel) pattern. SLMs have an expanding role in several optical areas where light control on a pixel-by-pixel basis is critical for optimum system performance. SLMs are typically used to control incident light in amplitude, phase, or the combination of both.

SLM Device Construction
Several parameters help define SLM characteristics. Pixel pitch is defined as the center-to-center spacing between adjacent pixels. Interpixel gap describes the edge-to-edge spacing between adjacent pixels.

Polarized light enters the device from the top, passes through the cover glass, transparent electrode and liquid crystal layer, is reflected off the aluminum pixel electrodes, and returns on the same path. Drive signals travel through the pins on the bottom of the pin-grid array package, through the bond wires, and into the silicon die circuitry. The voltage induced on each electrode (pixel) produces an electric field between that electrode and the transparent electrode on the cover glass. This field produces a change in the optical properties of the LC layer. Because each pixel is independently controlled, a phase pattern may be generated by loading different voltages onto each pixel.

Why choose our Reflective SLMs?

High Voltage Backplanes = Fastest Response Times
Our SLMs use custom backplanes, and proprietary drive schemes to achieve response times down to 1 ms (wavelength dependent). Most other liquid crystal spatial light modulators utilize display backplanes built with standard Nematic liquid crystal, limiting response time to >30 ms.

Highest Phase Stability Commercially Available –
Our backplanes are custom designed to allow high refresh rates (up to 6 kHz), and direct analog drive schemes. Refreshing the voltage at the pixel at rates far surpassing the response time of the liquid crystal ensures high temporal phase stability. Further, use of direct analog drive schemes, as opposed to digital dithering, reduces optical flicker as low as 0.1% (0.001 π radians). Low Inter-pixel Cross Talk - Our backplanes are custom designed to offer high voltage at the pixel (5 – 12 V), and a large pixel pitch. Further, our SLMs are built with our proprietary liquid crystal which minimizes the required thickness of the LC layer in the SLM. By maximizing the ratio of pixel pitch to LC thickness we are able to offer SLMs with minimal inter-pixel effects.

Broad Wavelength Capabilities – we are the only SLM supplier capable of offering SLMs designed for use from UV (>365 nm) up to the LWIR (8 - 12 µm). Analog is Better - All SLMs have been designed for phase modulation. Unlike many display LCoS backplanes which require a pulse width modulation (PWM) scheme, our backplanes utilize analog voltages at each pixel. This results in a very stable phase response over time.

High Bit Depth Controllers - we offer 8, 12, and 16-bit controllers to provide the most linear resolvable phase levels commercially available (up to 500). Fast transfer speeds from the computer to the SLM are offered up to 2 kHz.
Overview

Polarized light enters the device from the top, passes through the cover glass, transparent electrode and liquid crystal layer, is reflected off the aluminum pixel electrodes, and returns on the same path. Drive signals travel through. There are 2 types of special light modulators: reflective analog SLMs and transmissive SLMs.

Reflective Analog SLMs: All of our liquid crystal on silicon (LCoS) backplanes incorporate analog data addressing with high refresh rates to provide the lowest phase ripple SLMs available. User’s can select standard or high speed liquid crystal for optimal performance. Liquid cooling systems are available to remove heat via the back of the SLM chip in order to maximize optical power handling capabilities:

Transmissive SLMs: All of our liquid crystal on glass (LCoG) SLMs enable simple optical systems when low pixel counts are sufficient. Users can select single-mask or configurations for phase or amplitude modulation, or a dual-mask configuration for combined phase and amplitude modulation.

1. Reflective Analog SLMs

1.1 Small 512 x 512 Reflective Spatial Light Modulators, – Entry Level – Educational – Economical

Our legacy SLM is now available as our E-Series model. It is ideally suited for labs with a limited budget or researchers who do not require the high speed features of our premium SLMs, yet still demand high performance. This entry-level SLM is affordably priced without sacrificing quality.

Our Liquid Crystal on Silicon (LCoS) Spatial Light Modulators (SLMs) are uniquely designed for pure phase applications and incorporate analog data addressing with high refresh rates. This combination provides user’s with the fastest response times and highest phase stabilities commercially available. We offer both transmissive and reflective SLMs in either one or two dimensions. Phase-only SLMs can also be used for amplitude-only or a combination of both.

The 512 x 512 SLM is good for applications requiring high speed, with synchronization / triggering capabilities. The optional dielectric mirror coating provides users with 100% fill factor, which increases optical efficiency.
Features:
• High speed
• Pure analog phase control
• High bit-depth controllers (high phase resolution)
• High reflectivity option
• High power handling
• Synchronization / Triggering
• Wavelengths from 400 – 1650 nm

Specifications:
Resolution: 512 x 512
Fill Factor: 83.4 - 100%
Array Size: 7.68 x 7.68 mm
Diffraction Efficiency*: 61 - 99%
Pixel Pitch: 15 x 15 µm
Controller: PCIe 8-bit, PCIe 16-bit, DVI 16-bit

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Wavefront distortion</th>
<th>Liquid crystal response time [standard / high efficiency] (ms)</th>
<th>AR coatings [Ravg&lt;1%] (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model E512/PDM512</td>
<td>Model HSP512/HSPDM512</td>
</tr>
<tr>
<td>405</td>
<td>λ/5</td>
<td>25 / 33.3</td>
<td>N/A</td>
</tr>
<tr>
<td>532</td>
<td>λ/7</td>
<td>33.3 / 45</td>
<td>7 / 10</td>
</tr>
<tr>
<td>635</td>
<td>λ/8</td>
<td>33.3 / 45</td>
<td>12 / 16.7</td>
</tr>
<tr>
<td>785</td>
<td>λ/10</td>
<td>55.5 / 80</td>
<td>17.2 / 22.2</td>
</tr>
<tr>
<td>1064</td>
<td>λ/10</td>
<td>66.7 / 100</td>
<td>10 / 16.7</td>
</tr>
<tr>
<td>1550</td>
<td>λ/12</td>
<td>100 / 130</td>
<td>20 / 28.5</td>
</tr>
</tbody>
</table>

* Diffraction efficiency of silicon backplane. Performance varies as a function of wavelength and pixel value.

Controller Models

<table>
<thead>
<tr>
<th>Model</th>
<th>PCIe 8-bit</th>
<th>PCIe 16-bit</th>
<th>DVI 16-bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller phase levels</td>
<td>256 / 8-bits</td>
<td>65536 / 16-bits</td>
<td>65536 / 16-bits</td>
</tr>
<tr>
<td>CPU to controller transfer time (computer dependent)</td>
<td>0.6ms</td>
<td>2.1ms</td>
<td>16.7ms</td>
</tr>
</tbody>
</table>

OverDrive Plus (ODP) for Ultra-High Speed Operation

The use of ODP has shown reductions of the liquid crystal response times by a factor of up to 8x through use of the transient nematic effect, phase wrapping, and regional calibrations. The base technology is the transient nematic effect, utilizing intermediate transition voltages beyond the target voltage needed to achieve the desired phase value. The second technology development is the use of phase wrapping, which is based on the cyclical nature of light wherein adding or subtracting 2π from any phase value in a hologram results in an equivalent hologram. Often times it is faster to switch from \( \phi_1 \rightarrow \phi_2 \pm 2\pi \) instead of switching from \( \phi_1 \rightarrow \phi_2 \). ODP automatically implements the faster of the two
transitions, based on the calibration data. The third technology development is the utilization of regional calibrations of an SLM. Because most optical applications require precision on the order of a fraction of a wavelength, nearly all SLMs will have some inherent phase errors across the aperture that may impact the performance of the optical system. OverDrive Plus utilizes the phase modulation capabilities of the SLM to calibrate these errors out of the reflected wave, while also utilizing the regional calibrations when determining the length of time required for the transient nematic effect on a pixel by pixel basis.

OverDrive Plus for Ultra-High Speed Modulations

Low Phase Ripple - Our Spatial Light Modulators are known for having the highest phase stability on the market. Our backplanes are custom designed with high refresh rates and direct analog drive schemes resulting in phase ripple less than 1% - 3% (depending on SLM model). Phase ripple is quantified by measuring the 1st order ripple as compared to the mean intensity while writing a repeating linear phase ramp to the SLM.

High Power Capability - our Spatial Light Modulators have been tested for compatibility with high power pulsed and CW lasers. In the measurements below, the optical response of the 512 x 512 pixel SLM was measured as the incident power was incremented up to a peak power density of 112 MW/cm². Thermal effects resulted in a reversible reduction in modulation depth, however no permanent damage was observed.

512x512 SLM tested at 1064nm
**Average power of 1W to 16W with a repetition rate of 1MHz, pulse width of 600fs, and 5.5mm beam diameter results in a peak power density of up to 112MW/cm², without dielectric mirror coating or active cooling**

### 1.2 Large 512x512 Reflective Spatial Light Modulators

This high voltage, large pixel SLM is optimized for high power applications requiring faster response times. The analog, high fill factor, high refresh rate backplane provides better optical efficiency and high temporal stability. Large pixels reduce pixel-to-pixel crosstalk.

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**High Efficiency Large 512 x 512 Spatial Light Modulator**

Our Liquid Crystal on Silicon (LCoS) Spatial Light Modulators (SLMs) are uniquely designed for pure phase applications and incorporate analog data addressing with high refresh rates. This combination provides user’s with the fastest response times and highest phase stabilities commercially available. We offers both transmissive and reflective SLMs in either one or two dimensions. Phase-only SLMs can also be used for amplitude-only or a combination of both.

The Large 512x512 SLM is good for applications requiring high speed, with synchronization / triggering capabilities. The large active area is also good for high laser power density applications.

**Features:**

10 Bukit Batock Crescent #07-02 The Spire Singapore 658079 Tel: 6316 7112 Fax: 63167113
http://www.SintecOptronics.com  http://www.sintec.sg  sales@sintec.sg  sales@SintecOptronics.com
• High speed
• Pure analog phase control
• High bit-depth controllers (high phase resolution)
• High power handling
• Synchronization / Triggering
• Wavelengths from 400–1650 nm, customization for MWIR or LWIR

Specifications
Resolution: 512x512
Fill Factor: 96%
Array Size: 12.8x12.8 mm
Diffraction Efficiency*: 92%
Pixel Pitch: 25x25 µm
Controller: PCIe 8/16-bit, DVI 16-bit

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Wavefront distortion</th>
<th>Liquid crystal response time [standard / high efficiency] (ms)</th>
<th>AR coatings [Ravg&lt;1%] (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model P512L/PDM512L</td>
<td>Model HSP512L/HSPDM512L</td>
</tr>
<tr>
<td>405</td>
<td>λ/5</td>
<td>3.0 / 4.5</td>
<td>N/A</td>
</tr>
<tr>
<td>532</td>
<td>λ/5</td>
<td>4.0 / 6.0</td>
<td>1.2 / 2.0</td>
</tr>
<tr>
<td>635</td>
<td>λ/6</td>
<td>4.5 / 7.0</td>
<td>1.7 / 3.0</td>
</tr>
<tr>
<td>785</td>
<td>λ/7</td>
<td>7.5 / 12.0</td>
<td>2.5 / 4.0</td>
</tr>
<tr>
<td>1064</td>
<td>λ/10</td>
<td>10.0 / 15.0</td>
<td>3.3 / 5.0</td>
</tr>
<tr>
<td>1550</td>
<td>λ/12</td>
<td>15.0 / 25.0</td>
<td>4.2 / 6.5</td>
</tr>
</tbody>
</table>

*Silicon backplane, performance varies as a function of mirror coating, wavelength and pixel value

Large 512x512 Controller Models

<table>
<thead>
<tr>
<th>Model</th>
<th>PCIe 8-bit</th>
<th>DVI 16-bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer to controller resolution</td>
<td>256 / 8-bits</td>
<td>65536 / 16-bits</td>
</tr>
<tr>
<td>Controller to SLM resolution</td>
<td>65536 / 16-bits</td>
<td>65536 / 16-bits</td>
</tr>
<tr>
<td>CPU to controller transfer time (computer dependent)</td>
<td>1.4ms</td>
<td>16.7ms</td>
</tr>
</tbody>
</table>

Ultra-High Speed Operation – The Large 512 x 512 SLM was designed to minimize the liquid crystal response time without the need for the OverDrive Plus approach developed for the Small 512 x 512 SLM. This native high-speed performance results in liquid crystal response times as fast as 1.2 ms, with computer-to-controller transfers speeds as fast as 1.4 ms, the combination provides a continuous 2π phase stroke at throughputs exceeding 700 Hz.

Two Controllers – PCIe or DVI. The high-speed performance is best achieved using a PCIe controller offering 8-bits per pixel image transfers from the computer to the controller. A hardware-based lookup table (LUT) converts the 8-bits to 16-bits prior to the analog conversion for the SLM chip. The result is a linear 2π phase stroke with a phase resolution of λ/256 at frame rates up to 714 Hz. The PCIe controller also offers both input and output triggering capabilities to ease synchronization with other equipment.

A DVI controller with 16-bits of analog voltage resolution from the computer to the SLM is also available. With this controller the SLM can easily obtain more than 1000 linear resolvable phase levels. This λ/1000 phase resolution can be maintained over a broad wavelength range by tuning the look-up-tables / calibrations for the incident wavelength. The frame rate is dependent upon the graphics card used (typically 60 – 200 Hz).

Low Phase Ripple – Our Spatial Light Modulators are known for having the highest phase stability on the market. Our backplanes are custom designed with high refresh rates and direct analog drive schemes resulting in phase ripple less than 1% - 3% (depending on SLM model). Phase ripple is quantified by measuring the 1st order ripple as compared to the mean intensity while writing a repeating linear phase ramp to the SLM.

1st order intensity when writing a phase ramp to the SLM
High Power Capability – Our Spatial Light Modulators have been tested for compatibility with high power pulsed and CW lasers. In the chart below, the optical response of the Large 512 x 512 pixel SLM was measured as the incident power was incremented up to a peak power density of 527 MW/cm², and an average power density of 518 W/cm². A liquid cooling system is also available to offset any thermal effects.

Large 512 x 512 SLM tested at 1064nm

Peak power density up to 527 MW/cm², average power density up to 518 W/cm², with a repetition rate of 123 Hz, pulse width of 8 ns, and 0.227 mm beam diameter, without dielectric mirror coating or active cooling. Damage occurred when the Ratio of Ein to Eout started climbing.

1.3 1920x1152 Reflective Spatial Light Modulators – New!

This SLM offers large format, high fill factor (high optical efficiency), high-speed (as fast as 1.4 ms), low phase ripple (.2 – 3%), high optical power handling (up to 15 GW/cm² peak power density), and high refresh rate. This analog, high voltage backplane produces very stable phase patterns, coupled with fast liquid crystal response times.

Our Liquid Crystal on Silicon (LCoS) Spatial Light Modulators (SLMs) are uniquely designed for pure phase applications and incorporate analog data addressing with high refresh rates. This combination provides user’s with the fastest response times and highest phase stabilities commercially available. We offer both transmissive and reflective SLMs in either one- or two dimensions. Phase-only SLMs can also be used for amplitude-only or a combination of both.
The 1920x1152 SLM is good for applications requiring high speed, high diffraction efficiency, low phase ripple and high power lasers.

**Features:**
- High resolution
- High speed
- Pure analog phase control
- High first order efficiency
- High reflectivity
- High power handling; Capable of >200 W/cm^2 with peak powers up to 15GW/cm^2
- Compact design
- Wavelengths from 400–1650 nm

**Specifications:**
- Resolution: 1920x1152
- Fill Factor: 95.7%
- Array Size: 17.6x10.7mm
- Diffraction Efficiency*: 88%
- Pixel Pitch: 9.2 x 9.2 µm
- Controller: PCIe 8/12-bit, HDMI 8/12-bit

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Wavefront distortion</th>
<th>Liquid crystal response time [standard / high speed] (ms)</th>
<th>AR coatings [Ravg&lt;1%] (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model P1920</td>
<td>Model HSP1920</td>
</tr>
<tr>
<td>405</td>
<td>λ/3</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>532</td>
<td>λ/5</td>
<td>9</td>
<td>1.4</td>
</tr>
<tr>
<td>635</td>
<td>λ/6</td>
<td>12</td>
<td>1.8</td>
</tr>
<tr>
<td>785</td>
<td>λ/7</td>
<td>19</td>
<td>2.5</td>
</tr>
<tr>
<td>1064</td>
<td>λ/10</td>
<td>25</td>
<td>3.3</td>
</tr>
<tr>
<td>1550</td>
<td>λ/12</td>
<td>33</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Silicon backplane, performance varies as a function of wavelength.
**High Phase Stability** - Our SLMs are known for having the highest phase stability on the market. Our backplanes are custom designed with high refresh rates and direct analog drive schemes resulting in phase ripple as low as 0.2% (0.002 π radians) for standard speed, and as low as 2% (0.02 π radians) for high-speed. Phase ripple is quantified by measuring the 1st order ripple as compared to the mean intensity while writing a repeating linear phase ramp to the SLM.

1st order intensity when writing a phase ramp to the SLM

**High Power Capability** - Our Spatial Light Modulators have been tested for compatibility with high power pulsed and CW lasers. In the graph below, the optical response of the 1920x1152 pixel SLM was measured as the incident power was incremented up to 15 GW/cm² peak power or 204 W/cm² average power. A liquid cooling system is available to reduce thermal effects. Optional water cooling system maintains consistent temperature and phase stoke when using high power lasers.

1920 x 1152 SLM tested at 1064 nm
Tested with a high power femtosecond industrial laser, 40W, 1-50MHz rep rate, <400fs to >10ps

HDMI 1920x1152 System Dimensions

PCle 1920x1152 System Dimensions:
1.4 1x12,288 Linear Reflective Spatial Light Modulators

The only high resolution linear array on a silicon backplane available on the market. The high refresh rate analog backplane provides excellent temporal stability. Our production process results in 100% fill factor, giving high optical efficiency.

**Features**
- High optical efficiency
- No mechanical motion
- High speed phase control
- Safe, low voltage operation
- User-friendly graphical interface

**Applications**
- Beam steering
- Diffractive optics
- Ultra-fast pulse shaping
- Spectral tuning / processing
- Programmable phase gratings
- Programmable amplitude gratings

**Specifications**
Resolution: 1x12,288
Fill Factor: 100%
Array Size: 19.66x19.66mm
Diffraction Efficiency*: 99%
Pixel Pitch: 1.6µmx19.66mm
Controller: PCIe 16-bit

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Liquid crystal response time (ms), Model P1920</th>
<th>AR coatings [Ravg&lt;1%] (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>532</td>
<td>4.5</td>
<td>400 - 850</td>
</tr>
<tr>
<td>635</td>
<td>5</td>
<td>400 - 850</td>
</tr>
<tr>
<td>785</td>
<td>8.5</td>
<td>600 - 1300</td>
</tr>
<tr>
<td>1064</td>
<td>15</td>
<td>600 - 1300</td>
</tr>
<tr>
<td>1550</td>
<td>30</td>
<td>850 - 1650</td>
</tr>
</tbody>
</table>

Model P12m288—λ(nm)–PT

Array size: 19.66x19.66nm
Design wavelength (nominal): 523 – 1550nm (Specify wavelength, λ in nm when ordering)
<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction efficiency (zero-order)</td>
<td>80 – 95% (max)</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>Up to 100%</td>
</tr>
<tr>
<td>Eternal window¹</td>
<td>Broadband AR coated for Ravg&lt;1.25% (450-865nm, 600-1300nm, 850-1650nm)</td>
</tr>
<tr>
<td>Fill factor</td>
<td>100%</td>
</tr>
<tr>
<td>Format</td>
<td>1 x 12288 (12288 active pixels)</td>
</tr>
<tr>
<td>Mode</td>
<td>Reflective</td>
</tr>
<tr>
<td>Steering angle</td>
<td>± 4-7°</td>
</tr>
<tr>
<td>Modulation</td>
<td>Controllable index of refraction</td>
</tr>
<tr>
<td>Phase levels (resolvable)</td>
<td>500 linear levels (min) for 2π phase stroke</td>
</tr>
<tr>
<td>Phase stroke (double-pass)</td>
<td>Typically 2π at user specified laser line (up to 6π available)</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>1.6 μm</td>
</tr>
<tr>
<td>Reflected wavefront distortion (rms)²</td>
<td>λ/3</td>
</tr>
<tr>
<td>Liquid crystal response time³</td>
<td>5-30 ms</td>
</tr>
</tbody>
</table>

Above specs are subject to change without notice. Please contact us for additional updates.

1. Custom AR coating options are available, including V-type for optimum optical efficiency at a single laser wavelength.
2. At nominal wavelength.
3. Phase stroke, temperature and wavelength dependent.

Dimensions:

Outline drawing showing front and side views of 1x12,288 Optical Head. Dimensions in millimeters.
1.5 E Series Reflective Spatial Light Modulators

The new E-series 512x512 liquid crystal on silicon (LCoS) SLM is ideally suited for labs with a limited budget or researchers who do not require the high speed features of our premium SLMs, yet still demand high performance. This entry level SLM is affordably priced without sacrificing quality.

Optically Flat
All the SLMs, including the E-Series, are designed and fabricated to be optically flat. Native flatness can be as low as $\lambda/8$. Using the SLMs wavefront correction capabilities, the compensated flatness can be...
better than $\lambda/12$ with simple Zernike polynomials, or flatter than $\lambda/50$ with regional calibration methods.

High Phase Stability
The E512 is designed with a backplane refresh rate of 6 kHz, and a direct analog drive scheme which provides unsurpassed phase stability. By refreshing each pixel at rates far surpassing the response time of the liquid crystal, we are able to offer a SLM with phase ripple as low as 0.20%.

16-bit DVI Controller
16-bit images can be transferred across the DVI interface at a rate supported by the graphics card used (60–200Hz). With 16-bits of analog voltage resolution, the SLM can be used to easily obtain more than 1000 linear resolvable phase levels. This $\lambda/1000$ phase resolution can be maintained over a broad wavelength range by tuning the look-up-tables / calibrations for your incident wavelength.

KEY FEATURES
Model: E512-\(\lambda\)-DVI

Entry-level
512 x 512 SLM
Pure analog phase control
High phase stability
16-bit DVI controller

<table>
<thead>
<tr>
<th>Feature</th>
<th>Entry level</th>
<th>High efficiency</th>
<th>High Speed</th>
<th>High resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E512-(\lambda)-DVI</td>
<td>-PDM512</td>
<td>-HSP512</td>
<td>-P1920</td>
</tr>
<tr>
<td>Pixel format</td>
<td>512x512</td>
<td>512x512</td>
<td>512x512</td>
<td>1920x1152</td>
</tr>
<tr>
<td>Pixel pitch (um)</td>
<td>15</td>
<td>15</td>
<td>15 or 25</td>
<td>9.2</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>405 532 635 1064 1550</td>
<td>405-1550</td>
<td>488-1550</td>
<td>405-1550</td>
</tr>
<tr>
<td>Liquid crystal response time (ms)</td>
<td>25.0 33.3 33.3 66.7 100</td>
<td>4-130</td>
<td>1.2-28.5</td>
<td>6-33</td>
</tr>
<tr>
<td>Zero order diffraction efficiency (%)</td>
<td>Up to 61</td>
<td>Up to 95</td>
<td>Up to 95</td>
<td>Up to 84</td>
</tr>
<tr>
<td>Phase stroke</td>
<td>$\geq 3\pi$ radians</td>
<td>$\geq 3\pi$ radians</td>
<td>$\geq 3\pi$ radians</td>
<td>$\geq 3\pi$ radians</td>
</tr>
<tr>
<td>Controller</td>
<td>DVI</td>
<td>DVI, PCIe 8-bit, PCIe 16-bit</td>
<td>PCIe 8-bit</td>
<td>HDMI</td>
</tr>
<tr>
<td>Array size (mm²)</td>
<td>7.68x7.68</td>
<td>7.68x7.68</td>
<td>7.68x7.68 or 12.8x12.8</td>
<td>17.6x10.7</td>
</tr>
<tr>
<td>Fill factor (%)</td>
<td>83.4</td>
<td>96 - 100</td>
<td>83.4 - 100</td>
<td>96</td>
</tr>
</tbody>
</table>

1st order intensity when writing a phase ramp to the SLM:
2. Transmissive Spatial Light Modulators

All of our liquid crystal on glass (LCoG) SLMs enable simple optical systems when low pixel counts are sufficient. Users can select single-mask or configurations for phase or amplitude modulation, or a dual-mask configuration for combined phase and amplitude modulation.

2.1 HEX-127 Spatial Light Modulator

Our two dimensional SLMs are designed for adaptive optics applications. A two dimensional array of Liquid Crystal Variable Retarders acts as a real time programmable phase mask for wavefront correction of a linear polarized source. Unwanted aberration effects are removed by introducing the opposite phase shift through the Hex SLM. The most common applications involve high-resolution imaging where viewing through an aberrant medium is unavoidable. Examples include astronomical imaging with ground-based telescopes and medical imaging through bodily fluids. High-energy laser users also benefit from active phase compensation for beam profile correction.

2.2 1x128 Linear Array Spatial Light Modulator

The linear SLM has a linear pixel array geometry. This system can be used to alter the temporal profile of femtosecond light pulses via computer control. Applications requiring these short pulses include analysis and quantum control of chemical events, optical communication and biomedical imaging. This linear SLM offers high fill factor, good transmitted wavefront distortion, and options for single or dual-plane for modulating phase, amplitude, or both simultaneously. These SLMs find use in other applications including Hadamard spectroscopy, optical data storage and wavefront compensation.

<table>
<thead>
<tr>
<th>Pixel format</th>
<th>Response time</th>
<th>Pixel pitch</th>
<th>Efficiency</th>
<th>Fill factor</th>
<th>Active area (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x128</td>
<td>35 – 70 ms</td>
<td>100 um</td>
<td>85 – 92%</td>
<td>98.0%</td>
<td>12.80 x 5.00</td>
</tr>
<tr>
<td>Hex</td>
<td>1 mm</td>
<td>90%</td>
<td>93.1</td>
<td>12,00Ø</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Spatial Light Modulator Controller

Our spatial light modulator controller allows for independent voltage control of up to 128 liquid crystal cells or pixels. The SLM Controller connects via USB cable to a Windows™ based computer. Supplied software allows for convenient setting of individual pixel retardance and for the programming of retardance profiles across a pixelated device. Custom software can be written using the included LabVIEW™ Virtual Instrument Library to allow for integration into custom applications.

Key Features
- High transmission
- Compact optical housing design
- Computer controlled
- Phase or amplitude modulation
### Optical head specifications

<table>
<thead>
<tr>
<th>Retarder material</th>
<th>Nematic liquid crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate material</td>
<td>Optically quality synthetic fused silica</td>
</tr>
<tr>
<td>Center wavelength</td>
<td>450-1800nm (specify)</td>
</tr>
</tbody>
</table>

#### Modulation range

<table>
<thead>
<tr>
<th>Phase (min) amplitude</th>
<th>$1\lambda$ optical path difference 0-100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retardance uniformity</td>
<td>&lt;2%rms variation over clear aperture</td>
</tr>
<tr>
<td>Transmitted wavefront distortion</td>
<td>$\leq \lambda/4$ (P-V @ 633)</td>
</tr>
<tr>
<td></td>
<td>[$\leq \lambda/10$ (RMS @ 633)]</td>
</tr>
<tr>
<td>Surface quality</td>
<td>40-20 scratch-dig</td>
</tr>
<tr>
<td>Beam deviation</td>
<td>&lt; 2 arc min</td>
</tr>
<tr>
<td>Reflectance (per surface)</td>
<td>$\leq 0.5%$ at nominal incidence</td>
</tr>
<tr>
<td>Dimension</td>
<td>7.00 x 2.96 x 0.74 in</td>
</tr>
<tr>
<td>Recommended safe operating limit</td>
<td>500W/cm², CW</td>
</tr>
<tr>
<td></td>
<td>300mJ/cm², 10ns, 532nm</td>
</tr>
<tr>
<td>Temperature range</td>
<td>10 - 45 °C</td>
</tr>
</tbody>
</table>

#### Controller specifications

| Output voltage          | 2kHz ac square wave digitally adjustable 0-10 Vrms |
| Voltage resolution      | 2.44mV (12 bit) |
| Computer interface      | USB |
| Power requirements      | 100 – 240VAC @ 47-63Hz, 1A |
| Dimensions              | 9.50 x 6.25 x 1.50 in |
| Weight                  | 2 lbs. |

*Note that the D31258 is included with the purchase of the SLM system*

#### Ordering information

<table>
<thead>
<tr>
<th>Name</th>
<th>Pixel geometry</th>
<th>Version</th>
<th>Part number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 128</td>
<td>98 $\mu$m x 4 mm linear</td>
<td>Phase</td>
<td>SSP – 128P - $\lambda$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amplitude</td>
<td>SSP – 128A - $\lambda$</td>
</tr>
<tr>
<td>Hexagonal 127</td>
<td>1 mm across flat</td>
<td>Phase</td>
<td>SSP – 127P - $\lambda$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amplitude</td>
<td>SSP – 127A - $\lambda$</td>
</tr>
</tbody>
</table>

*Please specify your operating wavelength $\lambda$ in nm when ordering. Custom SLM sizes and formats are available*

#### Optional polarizers

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength range (nm)</th>
<th>Part number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible</td>
<td>450 - 700</td>
<td>SDP – VIS</td>
</tr>
<tr>
<td>Near infrared</td>
<td>775 – 890</td>
<td>SDP – IR1</td>
</tr>
</tbody>
</table>

### 3. Optics Kit

Includes optics & mounts for simple phase or amplitude experiments. Available pre-aligned and ready to use over 405 - 1550 nm. Available with optional camera and laser.
Spend your time on important research rather than designing an optical system for your SLM. The SLM Optics Kit provides you with a set of optics and cage-mount components enabling the user to start research with the SLM system immediately. The kit includes a Half-Wave Retarder, a pair of Linear Polarizers, lenses, and all necessary mount hardware, including a custom adapter plate to quickly align the SLM system to the optics in an off-axis configuration. Optional items are also available including a laser, beam expander optics, and a camera. This approach provides optimum efficiency with minimal design effort.

Optics Kit includes:
- Polarizers and waveplates
- Beam expander
- Lenses
- Tip/tilt stage
- Base plate and posts
- Laser and camera (optional)

4. 1-Photon SLM Microscopy Kit
The 1-Photon SLM Microscopy Kit is a scan-less SLM-based epi-fluorescence upright microscope that enables three dimensional calcium imaging and/or photoactivation of neurons in brain slices. The microscope can be used to excite and monitor activity of neuronal ensembles, enabling studies of neuronal circuit activity both in vitro and in vivo. Add-on to existing microscope or use as stand-alone microscope.

**KEY FEATURES**

- Scan-less SLM-based
- Fully functional programmable excitation system
- Brightfield and/or Epifluorescence microscope
- 3D calcium imaging capability
- Point and click software to define excitation patterns

**5. Optical Tweezers Cube**

Our cube provides researchers with a portable, stand-alone, optical tweezers system just one cubic foot in size. This compact instrument allows a user to optically trap and thus physically manipulate hundreds of microscopic objects in three dimensions (3D) using computer control to set and move each optical trap independently.
Optical trapping can be used to manipulate objects ranging in size from 10’s of nanometers to 10’s of microns and objects with a variety of material characteristics. Trapping examples include cellular organisms, dielectric spheres, metallic spheres, metallic nanoshells, carbon nanotubes, air bubbles, and even water droplets in air.

One application of the CUBE includes biological research. This tool enables measurements of cell properties and controlled studies of how cells interact with foreign objects. Another application example is trapping metallic objects and carbon nanotubes for engineering materials with unique thermal and electrical properties.

KEY FEATURES
- Complete optical trapping system
- 3D particle manipulation using holographic beam control
- 100’s of traps (demonstrated 400)
- High temporal trap stability
- Spatially uniform trapping across 200x200 micron field of view
Application Notes: Spatial Light Modulators

3D Mapping of Neural Circuits In Vivo Opens the Window on Neurological Disease

Modifications with SLMs to existing two-photon microscopes can provide noninvasive probes deep within the cortex.

Despite extensive research, brain function and neurological diseases are poorly understood. Complexities arise from the quantity of neurons in the brain and from the densely interconnected networks of intermixed cell types. Tools neuroscientists have traditionally relied upon include the patch clamp, which probes electrical activity of a single neuron, and fMRI, which images activity in volumes containing millions of neurons.

These approaches target two vastly different scales. However, it is possible that the brain functions through firing patterns in neural circuits and that neurological disease is the result of alterations to the physical structure of circuits or circuit dynamics. These circuits exist at an intermediate scale that neither patch clamp nor fMRI can readily address. In order to give neuroscientists a range of tools to study brain function, there is a need for methods that noninvasively probe the underlying microcircuitry in the brain with single-cell resolution.

Figure 1. By manipulating the wavefront of a single incident beam, the spatial light modulator (SLM) can be used to superimpose lens and grating functions with weighting functions to redirect light to arbitrary locations to simultaneously create hundreds of focal points within a 3D volume.

Over the last decade, calcium imaging and photoactivation have emerged as solutions to this problem, providing all-optical means to monitor and manipulate circuit activity. Calcium imaging uses calcium indicators that bind with calcium to alter the fluorescence characteristics of neurons. When a neuron fires, there is an uptake of calcium into the cell body. If the firing neuron is illuminated with an excitation source during the firing event, then the fluorescence emission increases, generating an optical response that corresponds to electrical activity.

Complementary to calcium imaging is photoactivation, which can use photosensitive proteins (optogenetics) or opto-chemical (caged) compounds to manipulate firing patterns either by causing neurons to fire or by silencing neurons. This combination of calcium imaging and photoactivation offers a means for neuroscientists to record the spatiotemporal dynamics of activity and map physical structure of circuits with single-cell resolution. However, without advanced microscopes for neuroscience, the benefits of calcium imaging and photoactivation cannot be realized.
Confocal microscopes have become a core technology for biology, but have fundamental limitations that hinder their use for neuroscience. The first is slow temporal resolution from raster scanning a laser through the sample to build an image pixel by pixel. Without the ability to parallelize excitation to arbitrary locations within a 3D volume, it is impossible to monitor firing patterns of multiple cells simultaneously. This is critical for mapping connectivity of neural circuits and understanding circuit dynamics.

The second limitation is two-dimensional imaging, which is inappropriate for studies of neural circuits. This restricts studies to a small subset of the neurons and limits the scope of the circuits that neuroscientists are trying to map and understand. The third limitation is confocal microscopy’s coupling of one-photon excitation with a pinhole to block out-of-focus fluorescence emission. This results in low signal from trivially low depths in strongly scattering and absorbing samples, such as neurons within the cortex.

Two-photon microscopy provides submicron lateral and axial excitation confinement without requiring a pinhole, and the longer wavelength simultaneously minimizes scattering. When coupled with spatial light modulators (SLMs), two-photon microscopes are capable of parallelized excitation for photoactivation and volumetric imaging. SLMs can come in a variety of forms, including micromirror arrays and liquid-crystal (LC)-on-silicon modulators.

In a two-photon microscope, the micromirror array is imaged to the sample so that pixels turned on reflect light to neurons for excitation, and pixels turned off reflect light to a block. This allows a simple method to illuminate cell bodies. Micromirror arrays also offer response times on the order of 20 kHz, far surpassing the current response time requirements of neuroscience. However, because the micromirror array is an amplitude modulator as opposed to a phase modulator, it is not possible to generate lens functions for probing activity in a 3D volume or to actively redirect light from pixels that are turned off to desired focal point locations in the sample.

These limitations are overcome through use of LC-SLMs in microscopes. The SLM acts as a programmable lens manipulating the wavefront of the excitation source. In its simplest form, the SLM can be used as a programmable prism, redirecting light to a single focal point with a lateral shift. By adding prism functions together, the SLM can be used to create multiple focal points within a 2D plane. Furthermore, by adding weighting functions and lens functions, the SLM can redirect light to hundreds of focal points with a programmable intensity in a 3D volume (Figure 1).

In two-photon microscopes, LC-SLMs enable multisite 3D scanless excitation for photoactivation, as well as high-speed volumetric imaging to record a volume of circuit activity. This combination provides neuroscientists with a toolbox for in vivo studies deep within the cortex to better understand the physical structure of neural circuits, the relationship of firing patterns, external stimuli and the resulting behavior, and how these processes are altered in the presence of neurological disease.

3D photoactivation

Traditional two-photon microscopes contain galvanometer-scanning mirrors used to raster scan the laser focus through the sample. The mirrors are conjugate to the back focal plane of the objective. The SLM is added to the system through an additional relay prior to the galvanometer scanning mirrors (Figure 2). The addition of the SLM and two lenses transforms the function of the microscope so that it can deliver light to any location in the field of view and simultaneously excite multiple 3D sites and use a fast camera to capture their responses.

Optical layout of a two-photon microscope with an SLM
In a typical experiment, the galvanometer mirrors raster scan the sample to find the location of cell bodies in the field of view. Holograms then are generated to modulate the wavefront of the source to illuminate individual neurons. This can be used to photoactivate specific cells to replicate firing patterns that have been identified or to manipulate firing patterns that have been observed. Following photoactivation, the response of the surrounding cells can be monitored to understand the impact of photoactivation on the response of the circuit.

When designing the microscope, there are several key criteria that should be considered. The resolution of the SLM determines the number of locations where light can be directed in the sample. The resolution and pixel pitch together determine the dimensions of the volume within the sample that the SLM can excite. Ideally, the SLM will have a small pixel pitch with high resolution so it can steer to wide angles without under-filling the objective and sacrificing the lateral and axial excitation confinement.

The temporal phase stability of the SLM also is important to ensure reliable excitation. This is particularly important when dividing the light among many neurons and operating near the minimum threshold for excitation. Finally, the response time of the SLM will have significant impact on replicating the spatiotemporal dynamics, which can occur at rates up to 1 kHz.

Volumetric imaging
The ability to manipulate firing patterns is critical to understanding circuit activity, but equally important is the ability to record the response of surrounding neurons at the highest possible frame rate. Traditional two-photon imaging systems build an image volume by mechanically scanning the objective and collecting 2D images (Figure 3). The time required to image the volume can be on the scale of minutes, which is sufficient for static samples. In neuroscience, the dwell time requirement coupled with indicators with limited brightness results in the inability of traditional two-photon imaging to monitor action potentials in complete neural circuits. This opens up the possibility of misinterpretation of action potentials because of the interaction of localized excitation with animal movement.

Comparison of Gaussian and Bessel imaging of a mouse dendritic spine

Figure 3. Comparison of Gaussian and Bessel imaging of a mouse dendritic spine (left). Scanning of a Gaussian focus coupled with dwell time requirements for fluorescence excitation leaves a small portion of the sample illuminated and an increased likelihood of activity occurring without fluorescence excitation. Bessel imaging monitors a volume at the same rate of 2D imaging with Gaussian illumination. The “Bessel module” easily integrates with existing 2P microscopes without software changes, enabling easy adaptation of existing microscopes and significantly enhanced capability (middle). A demonstration of the Bessel module used for imaging inhibitory neurons in a mouse. With Gaussian imaging, a series of 2D scans are required to build the 3D projection, but the Bessel module enables imaging the entire volume without axial scanning (right). Courtesy of Na Ji, Janelia Research Campus.

One solution for high-speed volumetric imaging, presented by Na Ji, group leader at the Janelia Research Campus of the Howard Hughes Medical Institute, uses a Bessel focus-scanning technology (BEST) that samples activity in a volume with hundreds of microns in each dimension in the equivalent time that a Gaussian two-photon microscope images a 2D plane6.

The module for 3D imaging is simple and widely compatible with existing microscopes, consisting of an SLM, a static amplitude mask and three lenses (Figure 3). The lenses relay the image of the SLM to the sample. The amplitude mask is a static patterned mirror that selectively transmits the first diffracted order. The optional flip mirrors at the entrance and exit of the module allow optical addition or removal of volumetric imaging so that structures can be imaged with traditional Gaussian illumination if desired. The use of SLMs here allows flexible generation of Bessel foci of varying lateral sizes, axial lengths and axial intensity distribution, permitting users to optimize BEST for specific samples.

Ji has demonstrated the approach for enabling discoveries for neurobiology by imaging the calcium dynamics of volumes of neurons and synapses in fruit flies, zebrafish larvae, mice and ferrets in vivo. Calcium signals in objects as small as dendritic spines could be resolved at video rates. High-speed volumetric imaging is a critical advancement for microscopes adapted specifically to the needs of the neuroscience community.

The combination of SLMs, two-photon microscopy, calcium imaging and photoactivation is leading to advanced tools for neuroscientists to monitor and manipulate the activity of neural circuits in the brain. The methods require minor modifications to existing microscopes, allowing researchers to inexpensively and readily adapt existing tools to support 3D photoactivation with high-speed volumetric
imaging. This significantly enhances capabilities of microscopes, providing a complete tool enabling studies of neural circuits, expanding the field of view, the depth and the temporal limits at which neuroscientists can monitor and manipulate circuit activity.