meadowlark optics
spatial light modulators

# User Manual

## XY Phase Series

## Spatial Light Modulator

## With 16-bit PCIe Controller


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# 1 Introduction

This User Manual covers the XY Phase Series of liquid crystal on silicon spatial light modulators (SLMs) now available from Meadowlark Optics. The manual instructs users on how to set up the PCI electronic hardware, optics, and operate the system software. SLM system setup is fairly complex, incorporating optical components, mounting and positioning hardware, drive electronics hardware, and a proprietary software interface. We strongly recommend that all users first read and familiarize themselves with the entire User Manual before initiating the setup and start up procedures.

## 1.1 Spatial Light Modulator Principles

An SLM is a device that modulates light according to a fixed spatial (pixel) pattern. The XY Phase Series SLMs convert digitized data into coherent optical information appropriate for a wide variety of applications, including beam steering, optical tweezers, diffractive optics, pulse shaping and more. These applications require modulators that can easily and rapidly change the wavefront of a coherent beam. By combining the electro-optical performance characteristics of liquid crystal materials with silicon-based digital circuitry, Meadowlark Optics now offers high speed SLMs that are also physically compact and optically efficient.

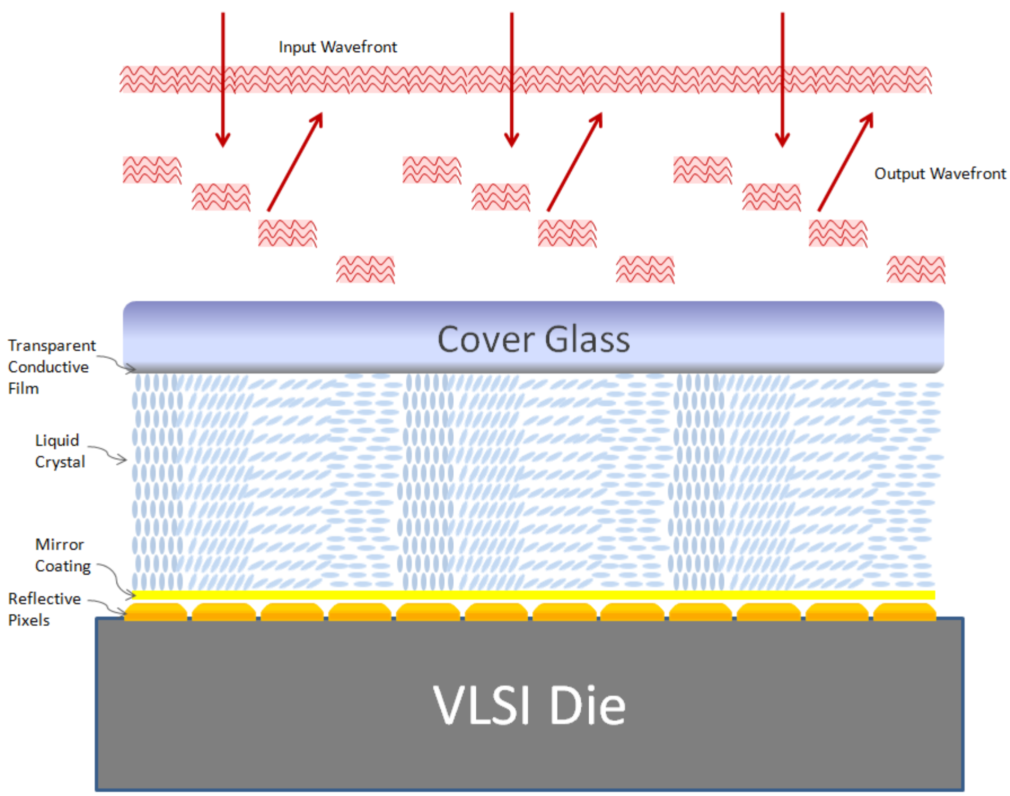



***Figure 1 ~ Cross sectional illustration of a liquid crystal spatial light modulator.***

Figure 1 shows the cross section of an LC SLM. Polarized light enters the device from the top, passes through the cover glass, transparent conductive film and liquid crystal layer, is reflected off the shiny pixel electrodes and returns on the same path. Drive signals from the driver boards travel through circuitry in the silicon backplane (VLSI die) to each pixel. The analog voltage induced on each electrode (pixel) produces an electric field between that pixel and 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.

If requested by the customer, a dielectric mirror coating is applied to the backplane of the SLM. This coating is normally centered at a wavelength specified at the time of ordering. The dielectric mirror coating prevents diffraction from the inter-pixel regions of the backplane, and increases the optical efficiency of the device.

## 1.2 Phase Modulation

The XY Phase Series of Spatial Light Modulators are fabricated with nematic liquid crystal, aligned in a homogenous configuration. Nematic liquid crystal has a variable electro-optic response to voltage. Figure 2 shows a simplified side view of a spatial light modulator's liquid crystal layer. When no voltage is applied to the LC, the molecules are parallel to the SLM coverglass and VLSI backplane. In this case, incident light will experience the largest difference between the extraordinary (ne) and ordinary (no) index of refraction. As the voltage applied to the liquid crystal is increased, the LC will tilt until the extreme is reached and the LC is nearly normal to the SLM coverglass and VLSI backplane. At this point the difference between the extraordinary and ordinary index of refraction is nearly zero.

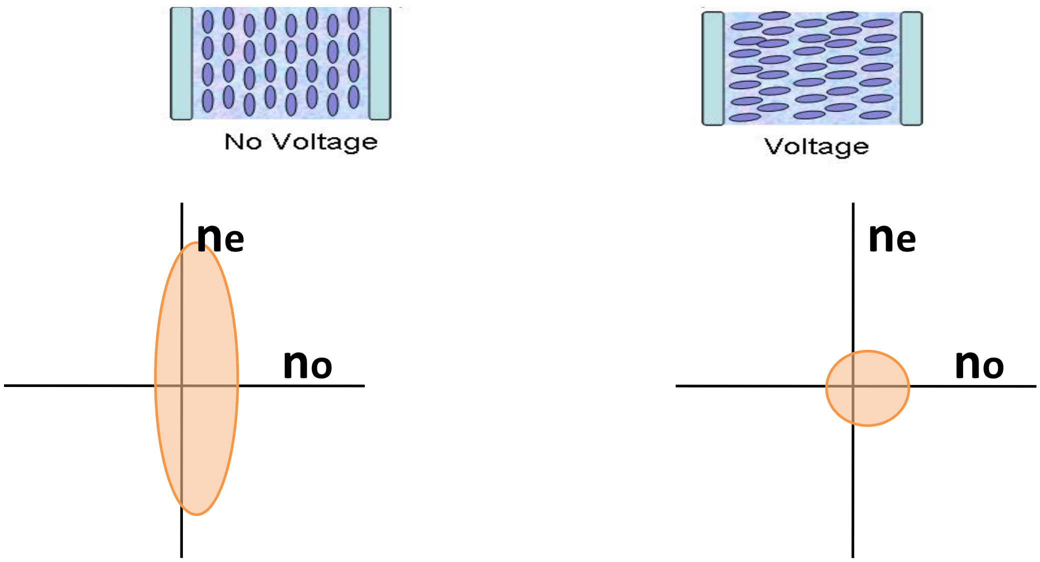



***Figure 2 ~ This diagram illustrates the liquid crystal orientation with respect to the coverglass and VLSI backplane as a function of applied voltage.***

***The molecules are parallel to the coverglass and backplane when no field is applied, and are nearly perpendicular to the coverglass and backplane when full field is applied.***

If light incident upon the SLM is linearly polarized parallel to the extraordinary axis, then a pure, voltage dependent phase shift will be observed. For example, if no voltage is applied to the pixel, the maximum phase retardation (typically a full wave at the design wavelength) will be applied. Likewise, if the pixel is programmed for maximum voltage, a minimum phase delay is applied. The result is a programmable phase on a per pixel basis.

Each of the SLM pixels is independently programmable to 65536 discrete voltage states, all providing phase modulation. The response of the liquid crystal within the SLM to the applied pixel value (voltage) is nonlinear. To account for this, each SLM is shipped with a custom look-up-table (LUT). When this LUT is applied to an input image, the result is a linear output phase response ranging from 0 to $2\pi$. Also, because of the nonlinear nature of the liquid crystal, 65536 phase levels are not achievable. The resolvable phase levels are much less, normally in the range of 500-1000.

## 1.3 Optical Test Setup

Depending on the application of the XY Phase Series SLM, many different optical setups can be used for either combined phase-amplitude mode or phase-only mode. Two examples of phase-only optical test setups are shown below.

### 1.3.1 Interferometer Setup

The first optical setup, illustrated in Figure 3, is a modification of a Twyman-Green interferometer (Handbook of Optics. Vol. 1, pp. 2.28-2.29). Here a monochromatic, collimated light source (i.e. laser beam expanded so it is larger than the diagonal of the SLM) passes through a non-polarizing beamsplitter such that the beam is divided into two beams, with nearly equal intensity. One of these beams illuminates the XY Phase Series SLM, while the other illuminates a Reference mirror. Each of these reflected beams is then recombined at the image plane of a lens. If the Reference mirror and the SLM are carefully aligned such that they are nearly coplanar, interference fringes will be visible at the image plane. A Camera is placed at the image plane in order to magnify the fringes for easier viewing. When the XY Phase Series SLM is driven with different phase patterns, dynamic interference fringes can be viewed. Analyzing the interference fringes will then provide insight into the phase modulation provided by the XY Phase SLM.

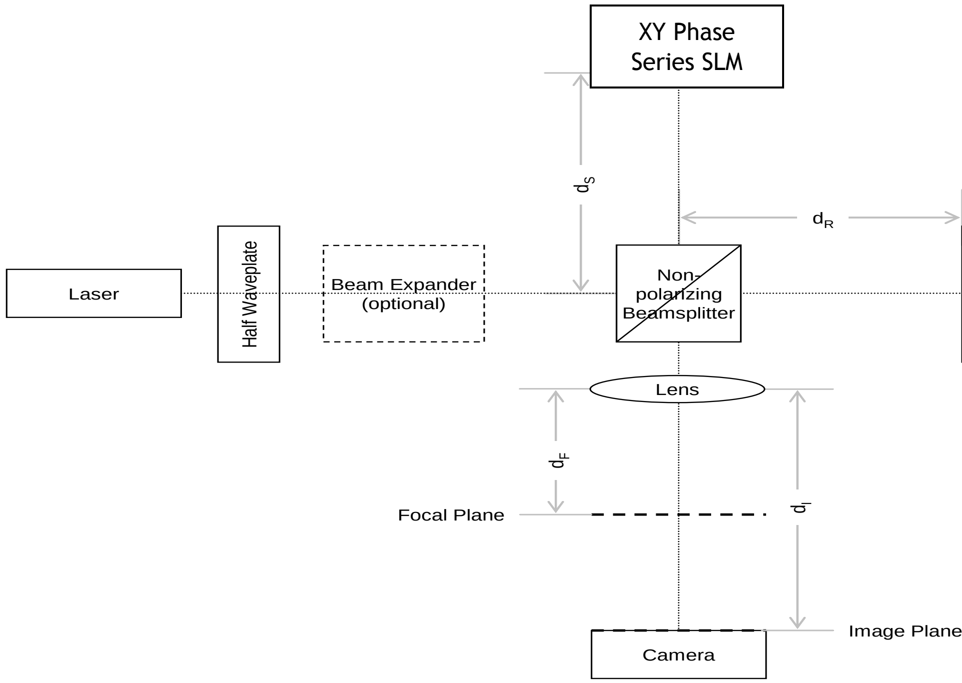



***Figure 3 ~ A Twyman-Green interferometer for testing a XY Phase SLM.***

In order to ease the alignment of the reference mirror and the XY Phase Series SLM in the Twyman-Green interferometer, place the camera or a card into the beam path at the Focal Plane of the Lens. There should be two spots visible, one from the Reference mirror and one from the SLM (there may also be very faint high-order diffraction spots from the SLM). If utilizing a beamsplitter cube, there are likely to be additional spots that are ghost images from the beamsplitter. When adjusting the tip/tilt of either the reference mirror or the SLM, the ghost spots will not move, but the true spots from the reference mirror and the SLM will move. Once the correct two spots are located, adjust the tip and tilt of the reference mirror and/or the SLM until these two spots are aligned on top of one another. Place the camera back in the Image plane, or remove the card, and interference fringes should be visible in the Image plane. By slowly adjusting the tip and/or tilt of just the reference mirror or SLM, the desired interference fringes should be readily obtained.

If working with a laser diode it is important to note that the coherence length of laser diodes are typically much shorter than the coherence length of a gas-discharge laser. With a Twyman-Green interferometer it is critical that both the SLM leg and the reference mirror leg have the same optical path length, ensuring that the short coherence length of a laser diode does not significantly reduce the visibility of the interference fringes. In order to ensure equal path lengths, set the camera such that it is focused onto the SLM – distinct features of the silicon backplane, such as individual pixels or the edge of the active area, should become sharp. Blocking the reference leg beam will likely be necessary in order to prevent crosstalk in the camera. Then move the block from the reference leg to the SLM leg and move the reference mirror closer to, or further from, the beam splitter until it is also in sharp focus on the camera. Since the reference mirror will likely not have any features with which to see the best focal point, look for focus of dust particles, or perhaps very carefully place a card onto the reference mirror such that it covers about half of the beam. The card edge can then be used as a guide to find the best focal position of the reference mirror.

There are a few important issues to remember whenever working with an SLM.

1. **Polarization** – The SLM is basically a variable single-order retardation plate, or wave plate. Like all wave plates, there is a fast axis and a slow axis. However with the XY Phase Series SLMs the index of refraction along the slow axis can be decreased electronically. When the light source is linearly polarized and parallel to the slow axis of the SLM, the result is phase-only modulation of the light source. If instead the light source were incorrectly oriented to be linearly polarized perpendicular to the slow axis, there would be no modulation observed with variable voltage. The use of a passive half wave plate will greatly facilitate achieving the desired polarization alignment.

2. **Diffraction** – The SLM has discrete, reflective pixel pads in order to isolate the electrical signals and allow phase patterns to be written into the SLM. As a result of these discrete pixel pads, there will be diffraction. This diffraction can easily be seen in the focal plane of the lens. There will be a very bright center spot ($0^{th}$-order), surrounded by a grid of spots becoming progressively dimmer as they get further from the $0^{th}$-order. In order to attain the maximum throughput, it is suggested to use as many of the diffracted spots, or orders, as possible. However, some applications do not allow the use of more than one order (typically the $0^{th}$-order).

3. **Dispersion** – Liquid crystal wave plates are not very achromatic because the index of refraction varies as a function of wavelength. This dispersion means that a device designed to provide a $2\pi$ phase stroke at one wavelength, will provide less than $2\pi$ phase stroke at a longer wavelength, and more than $2\pi$ phase stroke at a shorter wavelength.

4. **Optical Quality** – Due to the very small pixel pitch of the SLM, it is important to use high quality optics. A single element lens will generally have too much spherical aberration to provide a good, sharp focus across the entire clear aperture of the SLM. As a result, it is recommended to always use at least a doublet lens. For the same reason, the longer the focal length of the lens, the better the resulting image at the image plane. In addition, the transmitted wavefront distortion of most beamsplitter cubes is typically $\sim\lambda/4$, contributing to unacceptable wavefront distortion at the image plane. The use of a beamsplitter plate in place of a beamsplitter cube could improve the wavefront distortion, but using a beamsplitter plate requires the use of a compensating plate in the reference leg of the Twyman-Green interferometer.

An off-axis setup, shown in Figure 4, is designed to maximize throughput by eliminating the non-polarizing beam splitter. A laser beam is incident on the SLM at a slight angle, reflects off of the reflective pixel pads, and then is imaged with a lens onto a camera. Please note that since this optical setup is not an interferometer, the actual phase modulation will not be visible on the camera. This optical setup is only shown to illustrate the concept of an off-axis system. The setup should be modified to meet the exact application requirements. The off-axis angle should be kept to a minimum in order to reduce crosstalk effects due to the beam traveling through more than one pixel region. Minimizing the off-axis angle also keeps the phase stroke closer to the designed value.

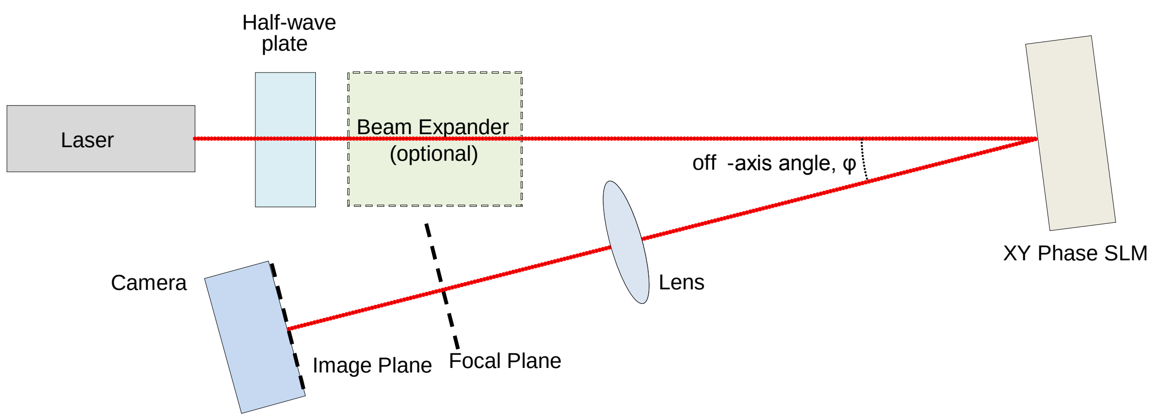



***Figure 4 ~ Off-axis optical setup for the XY Phase Series SLMs.***

# 2 System Shipping Contents

Your system contains the following components:

- PCIe Controller
- One-Stop PCIe card
- SLM Optical Head
- User Manual
- USB Flash Drive
- Cables:
    - 3 ft. 80-pin ribbon cable.
    - 10 ft. PCIe cable
    - Power cable


***Figure 5 ~ SLM system components.***

# 3 System Setup

**CAUTION**

**To minimize potential installation issues do not install any hardware until after the software has been fully installed.**

The diagram in Figure 6 shows the hardware for one SLM system. The PCIe host adapter board (C) plugs into a standard PCIe bus slot on an IBM-compatible personal computer (PC). This board provides an extension of the PCIe signals. When the system is running, control commands and digital image data are sent from the PCIe host adapter board through the PCIe cable (D) to the PCIe Driver Module (E) where it is converted to an analog data signal. The analog data signals are then transferred through the ribbon cable (F) to the Op-Amp board (on the SLM head assembly (G)) where they are amplified to appropriate levels.

The hardware should be installed before the software.

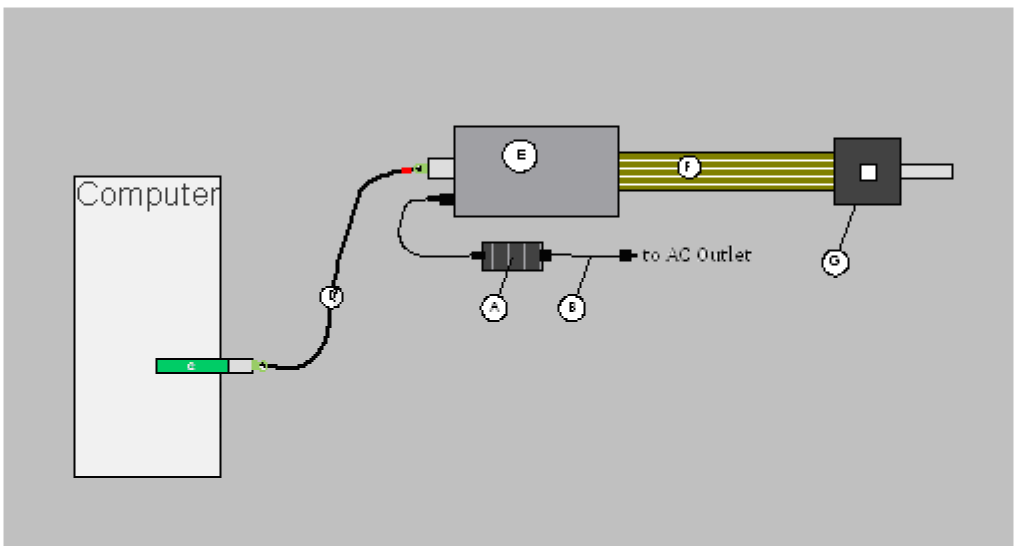



***Figure 6 ~ Top level diagram illustrating major components of the Meadowlark SLM system contents.***

## 3.1 Software Installation

### *3.1.1 Minimum System Requirements*

In order to effectively utilize your SLM system some basic computing hardware is required. The following components are essential to properly achieve the full performance of your SLM system.

- IBM-compatible personal computer (PC), Pentium® -based (100 MHz minimum) system.
- USB Flash Drive
- Available full-length PCI slot.
- Windows®-based computer operating system (Windows 7 or Windows 8).
- Mouse or other pointing device.
- Display monitor with 800 x 600 pixel format (minimum) and 256 colors (or more).

### *3.1.2 Software Installation Instructions*

The software on the USB Flash Drive contains the executable code necessary to operate the SLM, as well as sample pattern files, sequence files, and various other support files. Please follow these steps to install the software prior to installing the hardware.

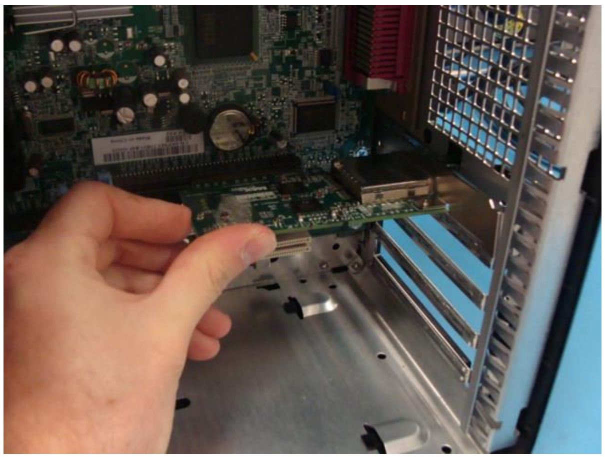
1. Insert the USB Flash Drive that came with your SLM system into the USB Port.
2. Double-click the setup installation file.
3. When the Install shield appears, follow the onscreen instructions to complete the installation.
4. When the installation is complete, eject the USB Flash Drive from the drive and store it away carefully.
5. Shut down the computer and install the hardware as shown in the step by step pictures in the Hardware Installation section of the guide.
6. After the hardware is installed, boot the computer. The device drivers should automatically install.

## 3.2 Hardware Installation

**CAUTION**

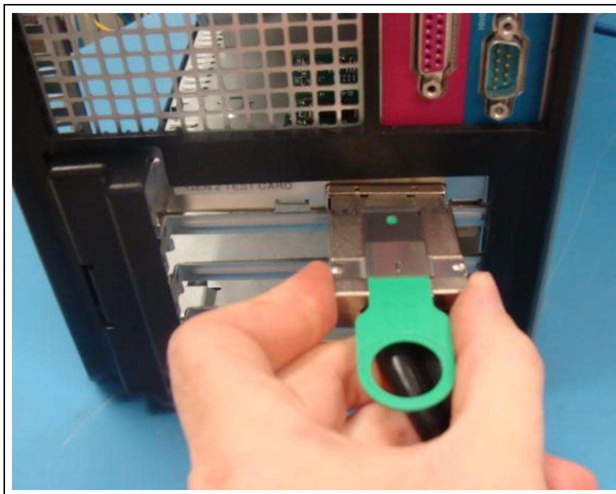
**Ensure that your computer is completely powered off prior to installing any hardware.**

**Do not power the computer on until ALL cables included with your SLM system have been properly connected.**



Remove the outside cover of your computer. Insert the PCIe Card into any unused PCIe slot. For the 16-bit system, the PCIe slot used needs to be at least x8. Ensure the card edge is lined up properly with the PC connector, do not force the board into place. Screw the mounting bracket of the PCI board to the back panel of the computer. This will prevent the board from coming loose, such as when connecting or disconnecting cables.

***Figure 7 ~ PCIe Card installation***



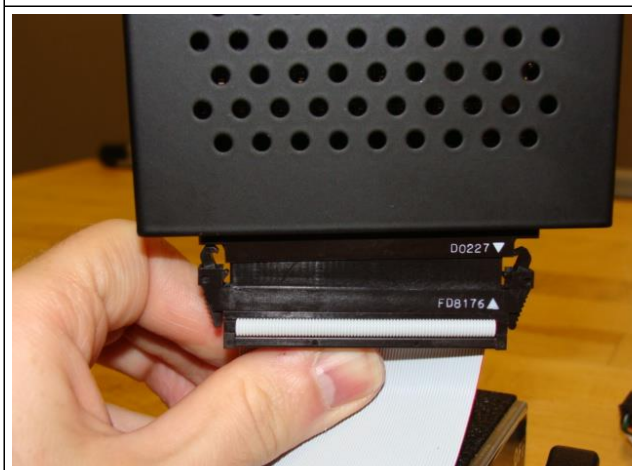
Attach one end of the PCIe cable to the PCIe card. Make sure that the cable is fully inserted and a click is heard. To remove the cable, gently pull back on the green tab and remove the cable connector from the PCIe card.

***Figure 8 ~ Attaching PCIe cable to PCIe card***


Attach the PCIe cable to the PCIe controller. Insert the cable until a click is heard verifying that the cable is fully connected.

***Figure 9 ~ Attaching the PCIe cable to PCIe controller***


Attach the ribbon cable to the PCIe controller. Line up the white arrows to ensure proper connection and push until a click is heard.




Connect the ribbon cable to the SLM. The white arrows need to line up for proper connection.

***Figure 10 ~ Attaching the ribbon cable***

Once the PCIe card is installed and the PCIe cable is securely fastened to both the PCIe card and the PCIe controller, power can be supplied to the controller. Make sure to supply power to the controller before turning the computer on.

***Figure 11 ~ Power the PCIe controller***

When the computer is booted, the drivers should automatically install. To verify that the drivers are installed, check the Device Manager. There should be a Jungo tab with two drivers underneath it; one being WinDriver and the other being PCIeDriver (not PCIe_64_Driver, as shown in in Figure 12).

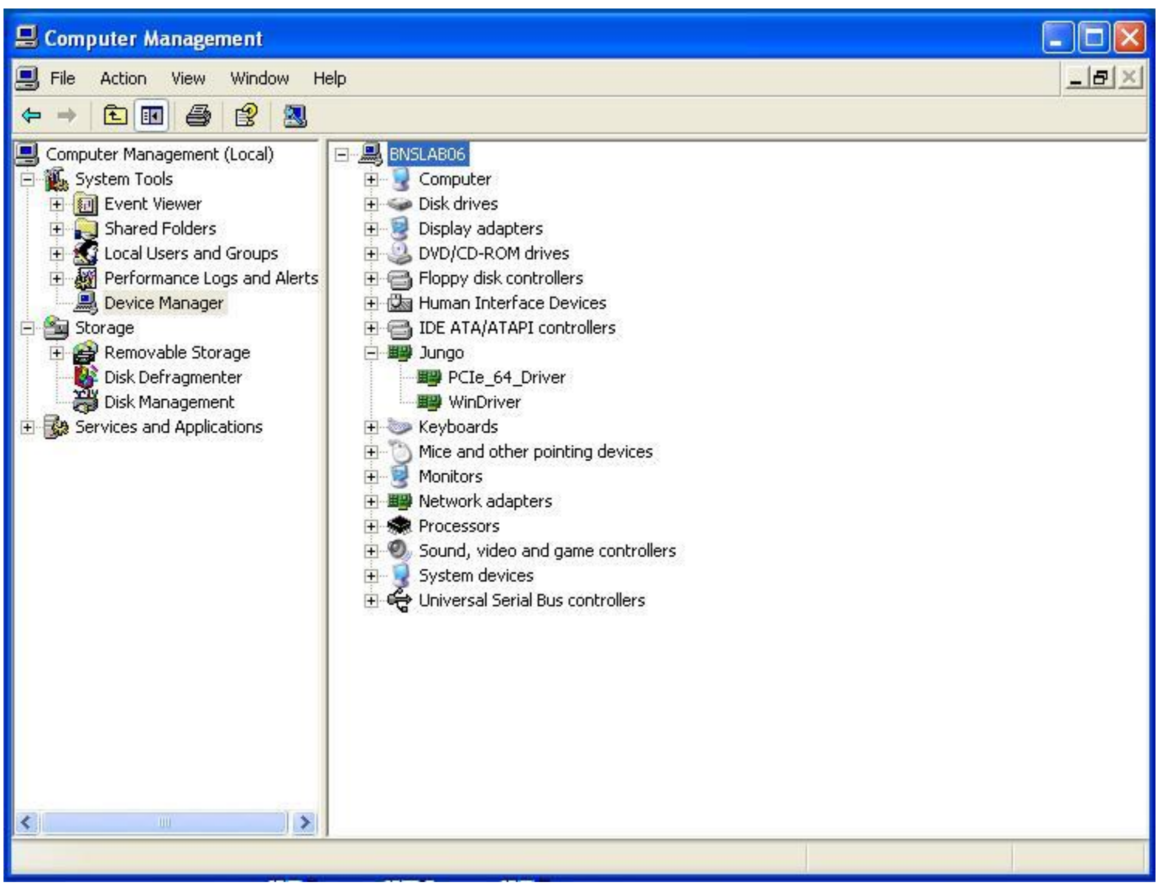



***Figure 12 ~ Device manager screen***

If the PCI_Driver is not viewable, it may be listed under System devices as a Standard RAM Controller, as shown in Figure 13. If this is the case, rebooting the computer should fix the problem and make the PCIe_Driver visible under the Jungo tab.

If rebooting does not update the 'PCI Standard RAM Controller' driver, then right click on this item and select to update the driver. In the Hardware Update Wizard at the prompt that says 'Can Windows connect to Windows Update to search for software', select 'No, not this time'. At the next window, select to 'Install from a list or specific location'. At the next window, select 'Don't search. I will choose the driver to install'. At the next window within the Model list box the PCIe_Driver option should be found. Clink on it, and proceed with the driver update. If it is not found, click on the background of the list box to un-select all items, and then click on the 'Have Disk' button. This will allow you to browse to C:\BLINK_PCIe\PCIeDriver.inf. If this also fails, then contact Meadowlark Optics support for further information.

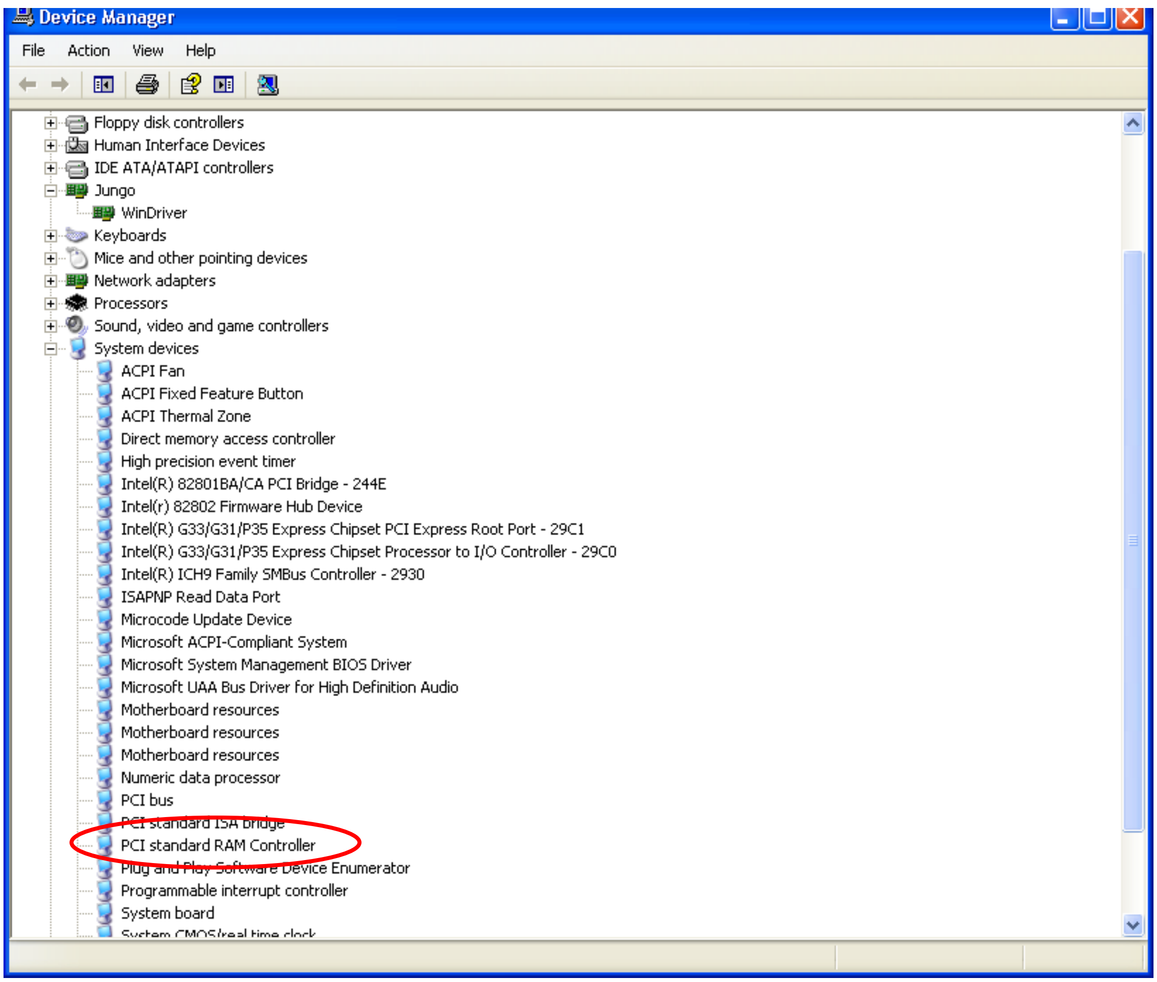



*Figure 13 ~ Device manager with PCIe_64_Driver not visible*

# 4 Software Operation

## 4.1 Introduction

The software that Meadowlark Optics developed to drive the XY Phase Series SLM is called Blink PCIe 16-bit and the current version of the software is 3.0. The software is used to load images to the SLM using a graphical user interface. This interface is shown in Figure 14.

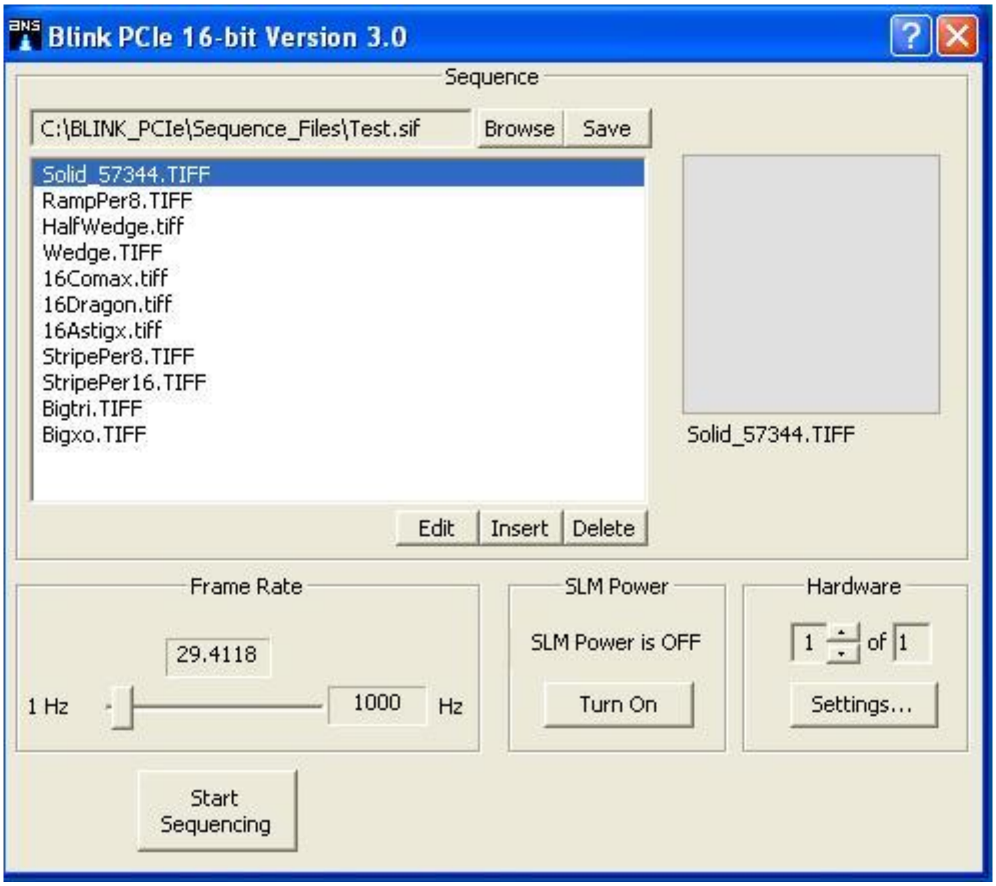



***Figure 14 ~ Blink PCIe 16-bit software interface***

To load an image to the SLM, click the SLM power button to turn the SLM on and then click on an image in the images list to load that image to the SLM. A new image can be loaded to the SLM by clicking on other image files or by using the arrow keys to scroll between images. For the 16-bit 512x512 or 256x256 SLM system, the images are 16-bit .tiff files. Multiple systems can be controlled from the software by setting the number in the hardware section to the desired number of hardware to be controlled. To sequence through the list of images, select the desired frame rate using the slider bar and then click the Start Sequencing button. The software will then sequence through the images at the selected frame rate.

### 4.1.1 Sequence list

The Sequence List is a predefined list of pattern files that will be loaded into the SLM (top to bottom). Figure 15 shows a sample sequence list. The file name of the current sequence list is shown in the upper left corner of the main window. To prevent losing the modifications, save the sequence file by clicking on the "Save" button in the upper right of the main software window – see Figure 14.

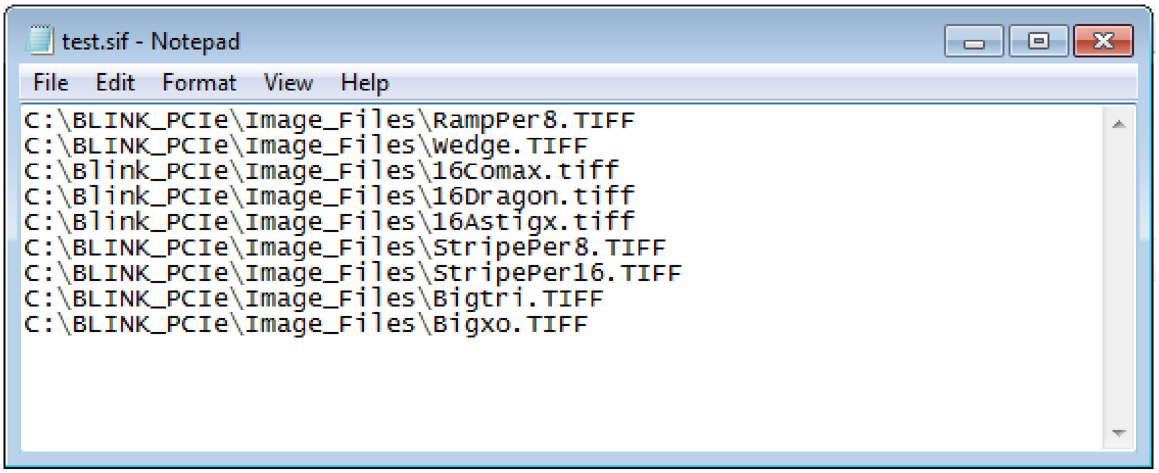



***Figure 15 ~ Sample sequence list***

### 4.1.2 LUT Files

The LUT (Look Up Table) is responsible for linearizing the phase response of the liquid crystal from 0 to 2pi. Meadowlark Optics generates a custom LUT for every SLM shipped, which is the default LUT when the software is first opened. However, the software also allows the user to both edit existing LUT files and to define new LUT files.

A LUT file is a text file with two columns. The first column is the input value and the second column is the value to which the input data will be mapped. Thus, the first column will always be 0 to 65535, so that every input value can be mapped to something else. The second column will increment to some value that will result in 2pi of phase shift up to 65535. This column will not increment linearly.

### 4.1.3 Board Setup

The board setup section of the dialog allows the user to set the True Frames, the LUT used, and the calibration image used. The Board Settings dialogue box is shown in Figure 16. The True

Frames value is the refresh rate of the liquid crystal and should not need to be changed as the value is set in-house for each system.

The calibration image is a text file that may be applied to correct for any wavefront distortions that are present on the SLM. The options below the calibration image link (WFC and NUC) are two different types of correction. WFC stands for wavefront correction and should be selected for phase SLMs. NUC stands for non-uniformity correction and is not used for the Phase Series SLM. The phase calibration file is a also a 16-bit .tiff image file. Because the SLM calibration file will be processed though the LUT, data ranging from 0 to 65535 represents one wave of phase shift.

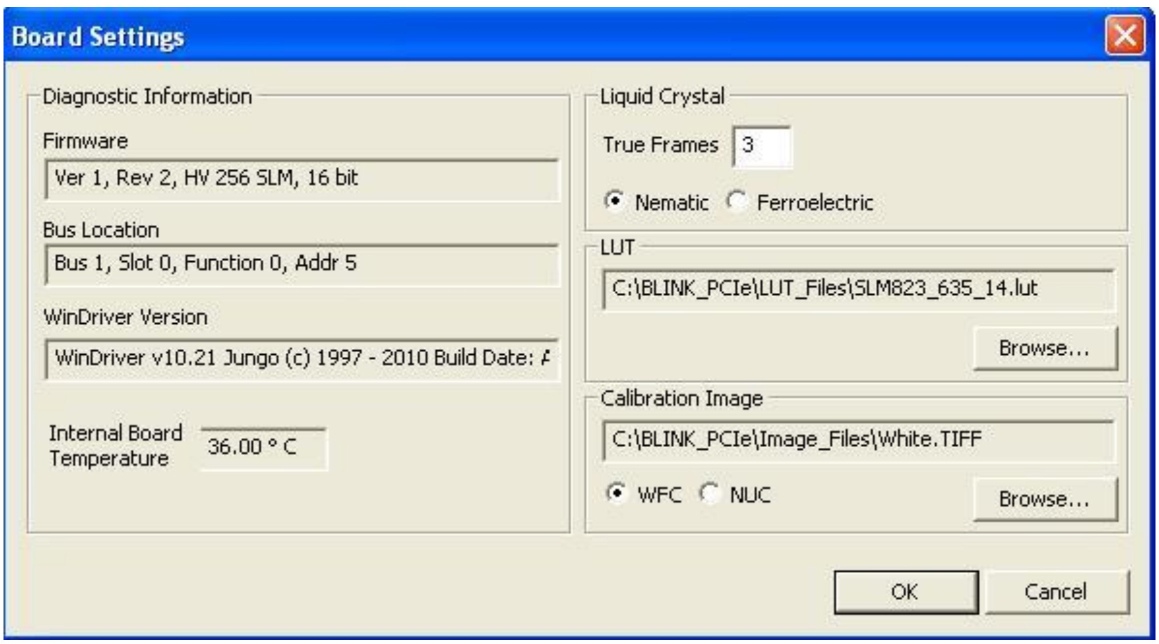



***Figure 16 ~ Board settings dialogue***

# 5 Mechanical Housing

The SLM Housing has vertical and horizontal micrometers for adjusting the tip and tilt up to ± 3°. The housing also allows the user to rotate the SLM about the optical axis by ~15°. A set screw (located beneath the flex, between the knobs) locks the rotation about the optical axis.

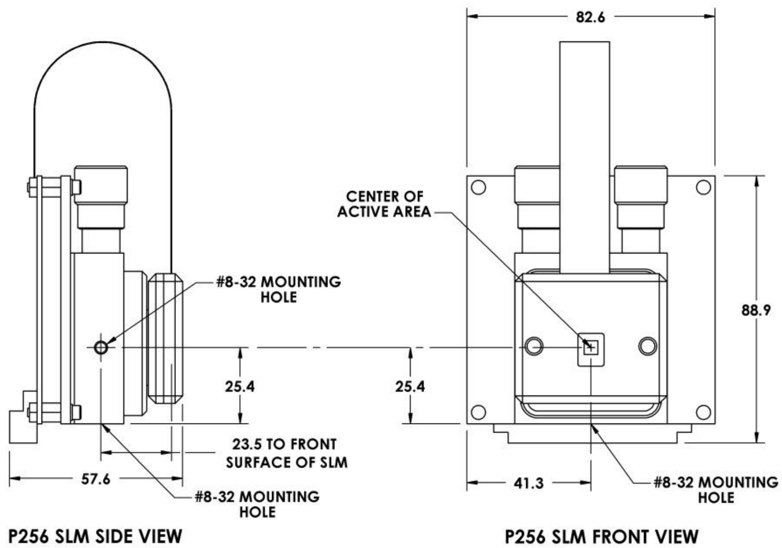



*Figure 17 ~ Outline drawing of the 256x256 SLM. Dimensions in millimeters.*

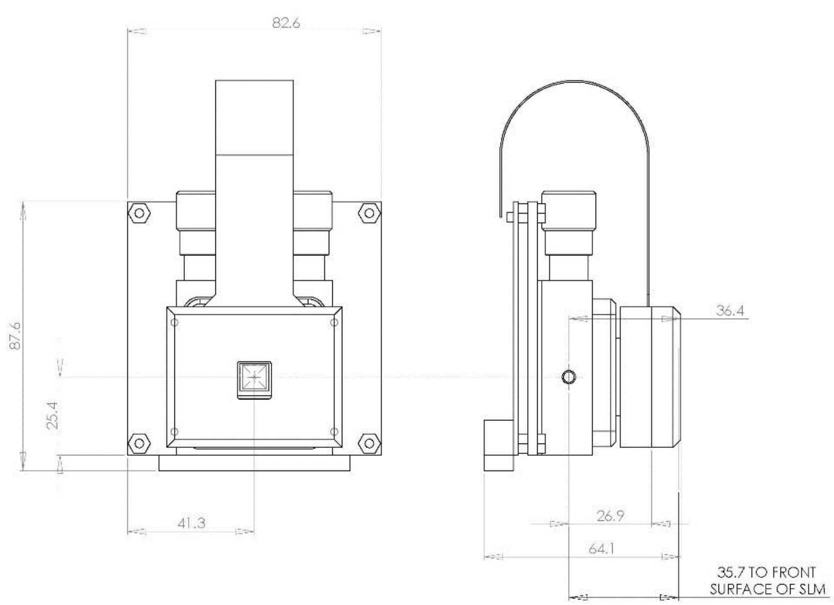



*Figure 18 ~ Outline drawing of the 512x512 SLM. Dimensions in millimeters.*

# 6 SLM care and cleaning

**CAUTION**

**Failure to follow the recommendations included in this document may violate your warranty. Always ensure all personnel involved in the handling of your SLMs have appropriate tools, equipment, and training prior to cleaning any SLM.**

**Never use acetone to clean your SLM. Acetone will cause irreparable damage to your SLM.**

**Never use pressurized air or nitrogen to clean your SLM. Pressurized air or nitrogen will destroy the bond wires that provide the electrical interface to the SLM.**

The SLM is shipped with a piece of paperboard covering the SLM aperture. This covering, or a similar covering, should be kept in place while the SLM is not is use to reduce the buildup of dust and debris on the SLM coverglass. When removing the aperture cover, or while the SLM coverglass is exposed, care should be taken to avoid any contact with the coverglass.

If dust or debris does contaminate the coverglass, gently remove them with a methanol soaked lens tissue. Take a small lens tissue or cleanroom wipe and soak a corner of it with methanol. Let the methanol evaporate until the lens tissue is just damp then gently wipe off the particles with the corner of the wipe. For more stubborn debris the methanol drag can be used. Fold a lens tissue several times until it is just small enough to fit inside of the SLM aperture. Soak the folded edge with methanol and let it evaporate until just damp. Line up the folded edge of the lens tissue with the edge of the glass, and drag the tissue straight across the glass. Never wipe the glass more than once with the same lens tissue as it will merely transfer dirt back onto the coverglass. Repeat as necessary.

If there is any dirt or contamination that cannot be removed, please contact the factory for additional cleaning instructions.

# 7 System Specifications

| | Model P512 – 0532 | Model P512 – 0635 | Model P512 – 0785 | Model P512 – 1064 | Model P512 – 1550 |
|---|---|---|---|---|---|
| **Array Size** | 7.68 x 7.68 mm | | | | |
| **Zero-Order Diffraction Efficiency** (standard) | 61.5% (maximum) | | | | |
| **Zero-Order Diffraction Efficiency** (with High Efficiency Mirror) | 90 - 95% (maximum) | | | | |
| **Duty Cycle** | Up to 100% | | | | |
| **External Window** - 600 to1300 nm also available (see chart on page 12) | Broadband antireflection coated for $R_{avg}$ < 1% (over 450 - 865 nm) | | | Broadband antireflection coated for $R_{avg}$ < 1% (over 850 - 1650 nm) | |
| **Fill Factor** (standard product) | 83.4% | | | | |
| **Fill Factor** (with High Efficiency Mirror) | 100% | | | | |
| **Format** | 512 x 512 (262,144 active pixels) | | | | |
| **Mode** | Reflective | | | | |
| **Modulation** | Controllable index of refraction | | | | |
| **Phase Levels** (resolvable) | 50 linear levels (minimum) for $2\pi$ phase stroke with PCI or PCIe 8-bit Controller | | | 100 linear levels (minimum) for $2\pi$ phase stroke with PCI or PCIe 8-bit Controller | |
| | 1,000 – 8,000 linear levels (minimum) with DVI 16-bit Controller | | | 2,000 – 16,000 linear levels (minimum) for $2\pi$ phase stroke with DVI 16-bit Controller | |
| **Phase Stroke** (double-pass) | Typically $2\pi$ ($\pi$ to $12\pi$ upon request) | | | | |
| **Contrast Ratio** (if used in Amplitude Mode) | 200:1 | | | | |
| **Pixel Pitch** | 15 x 15 µm | | | | |
| **Spatial Resolution** | 33 lp/mm | | | | |
| **Reflected Wavefront Distortion - RMS** (standard) | λ/3 @ 532 nm | λ/4 @ 635 nm | λ/5 @ 785 nm | λ/6 @ 1064 nm | λ/8 @ 1550 nm |
| **Reflected Wavefront Distortion – RMS** (PhaseFlat) | λ/12 @ 532 nm | λ/15 @ 635 nm | λ/20 @ 785 nm | λ/20 @ 1064 nm | λ/20 @ 1550 nm |
| **Standard Liquid Crystal** Response Time / Switching Frequency | ≤ 33.3 ms / ≥ 30 Hz | ≤ 33.3 ms / ≥ 30 Hz | ≤ 55.5 ms / ≥ 18 Hz | ≤ 66.7 ms / ≥ 15 Hz | ≤ 100 ms / ≥ 10 Hz |
| **High Speed Liquid Crystal** Response Time / Switching Frequency | ≤ 7 ms / ≥ 142 Hz | ≤ 12 ms / ≥ 83 Hz | ≤ 17.2 ms / ≥ 58 Hz | ≤ 10 ms / ≥ 100 Hz | ≤ 20 ms / ≥ 50 Hz |
| **High Efficiency with High Speed Liquid Crystal** Response Time / Switching Frequency | ≤ 10 ms / ≥ 100 Hz | ≤ 16.7 ms / ≥ 60 Hz | ≤ 22.2 ms / ≥ 45 Hz | ≤ 16.7 ms / ≥ 60 Hz | ≤ 28.5 ms / ≥ 35 Hz |
| **Wavelength Range** | 515 – 585 nm | 615 – 700 nm | 760 - 865 nm | 1030 - 1170 nm | 1505 - 1650 nm |

Above specifications are subject to change without notice. Please contact Meadowlark Optics for additional updates and wavelength-specific data.

**Thank you** for purchasing a Meadowlark Optics Spatial Light Modulator.

For additional product and company information, please contact:

*Meadowlark Optics, Inc.*
*5964 Iris Parkway*
*P.O. Box 1000*
*Frederick, CO 80530*

*Telephone: 303-833-4333*
*Fax: 303-833-4335*
*Website: www.meadowlark.com*

Please feel free to contact us with any questions you may have as well as to leave feedback about your device.

For questions regarding customer support for Meadowlark SLM products, please contact us by telephone or by e-mailing slmsupport@meadowlark.com

For questions regarding purchasing and pricing of additional Meadowlark SLM products, please contact us by telephone or by e-mailing sales@meadowlark.com