# Alignment + Aberrations + Amplitude Modulation

## Part *A*: Alignment (Adjust the input polarizer to limit beam intensity.)

After reading the linked material above, you are required to complete **Parts 1 and 3**, attempting to align optical elements so as to minimize aberrations: the optic axis of each **lens** should be aligned with the grid of the optical breadboard, as a fiducial reference: you will learn to create "cloned" apertures (set to the identical heights with respect to the optical breadboard), and to "walk" a laser through such a pair of apertures, to ensure that the beam is parallel to the optical table, and is aligned along a set of holes. Once that initial alignment exercise is completed, you add in your lenses, in a manner designed to minimize tilt and displacement from the optic axis. A pair of lenses separated by the sum of their focal lengths serves as a beam expander. Ideally, the output of this telescope will be neither converging nor diverging; when you believe your beam is "collimated," *double check*, by using a shear-plate collimation tester.

## Part *A′*: Aberration

After brief readings about Spherical Aberration, Coma and then Astigmatism, Curvature of Field, and Distortion, engage in qualitative observations, sending your expanded beam through a variety of *hand-held* lenses, in an exercise that is aimed at exploring, and *describing* how various kinds of lens misalignments (*e.g.*, tilt? lateral displacement from the optic axis? misplacement of your telescope lenses along the optic axis? *etc.*) yield distinct types of *aberrations* in the *nominal* focal plane of your hand-held lens. (Again, adjust the input polarizer to limit beam intensity.)
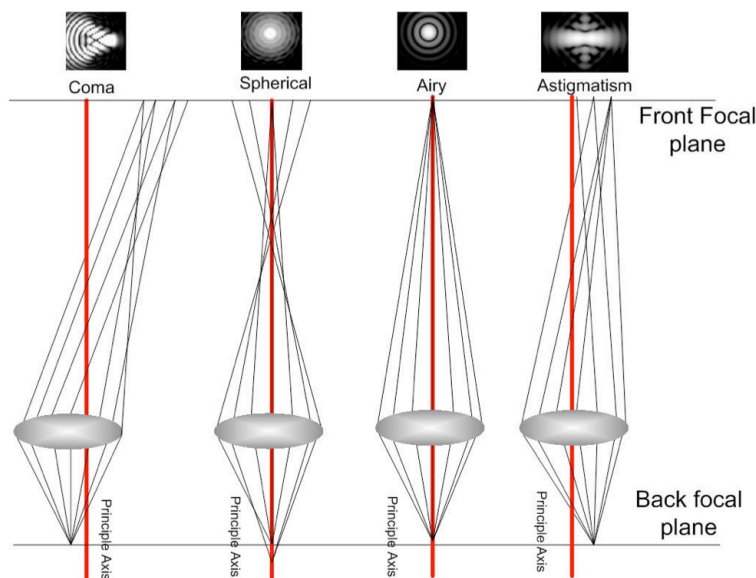


Fig. 1. Ray-tracing diagrams by W.M. (Steve) Lee, now at The Australian National University.

# Part *A″*: Amplitude Modulation — and calibrating the SLM's phase shift

Our SLMs are driven by an 8-bit circuit, allowing you to select from $2^8 = 256$ discrete voltage levels that can be applied to any individual pixel, controlling the *tilt* of the liquid crystal molecules. However, your computer can be set up to treat the SLM as if it were a traditional display monitor, albeit one that can only display a *grayscale* image, where each pixel is given a grayscale value between zero (black) and 255 (white). That is, a computer cannot tell the difference between a regular display monitor and these Digital Optical devices. You just set up your computer by telling it how many pixels to address, and the refresh rate (*e.g.*, for the Jasper EDK SLM, 1920 pixels × 1080 pixels, at 30 Hz). That said, an SLM is really **not** a computer monitor: the liquid crystal solution is simply a **transparent oil**. Adjusting the orientation of those molecules merely *retards* one component of the reflected light, and is not anything that your eyes (which, on their own, lack polarization sensitivity) can directly detect. So, the SLM acts like a "secret monitor," which you can only *decode* through the use of additional polarization optics.

You use the SLM by telling the computer to display a grayscale image on the "second monitor." Calibrating the SLM amounts to creating a *look-up table* that maps, for each applied "grayscale level" (0 - 255) displayed by the computer, the phase throw generated. This week, you will calibrate the SLM by adding polarization optics configured to provide amplitude modulation. In a later lab you will repeat your calibration via an independent experiment, where your added polarization optics will be configured to provide phase-only modulation.

### Step 1: Finding the SLM's intrinsic axes

Before we can properly configure the added polarization optics, we first need to determine the orientation of the extraordinary axis of the SLM.
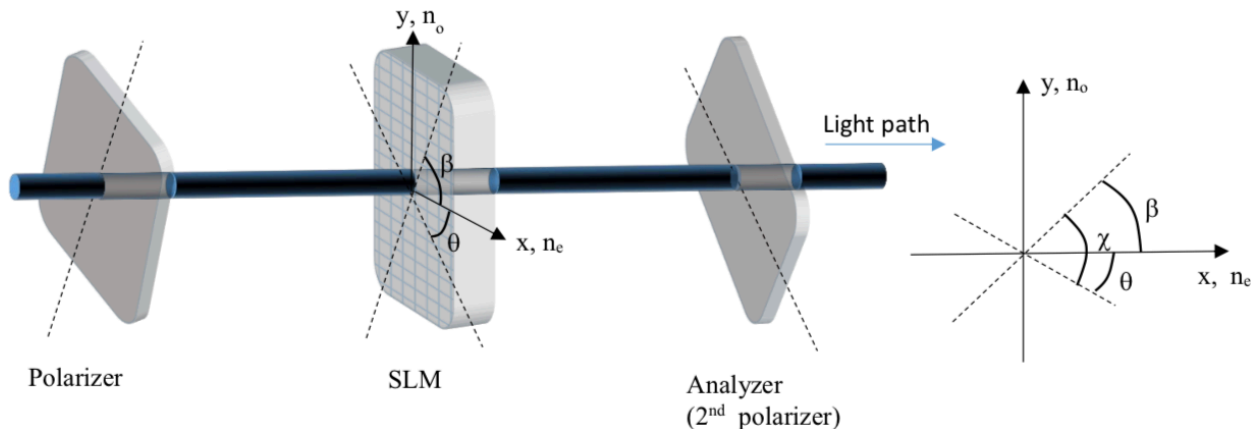


Fig. 2. In this **Polarizer + SLM + Analyzer** schematic, the *x*- and *y*-axes are fixed by the SLM orientation, which differs *significantly* from the horizontal and vertical directions in the lab. [Fig. credit: Lowell McCann, UW-River Falls]

Via *Mathematica*, we predict the transmissivity of a **Polarizer + SLM + Analyzer** system to be:

$$T = \cos^2(\theta - \beta) - \sin(2\theta)\sin(2\beta)\sin^2\left[\frac{\pi\ell}{\lambda}\left(n_e - n_o\right)\right] \qquad (1)$$

Here, $\beta$ is the angle of the input polarizer with respect to the extraordinary axis of the SLM, while $\theta$ is the angle of the analyzer with respect to that axis. If the polarizer and the analyzer both are aligned with the extraordinary axis of the SLM, then $\beta = \theta = 0°$, yielding $T = 1$ no matter how $n_e$ changes with the displayed grayscale level. That's a useful starting point: to **determine the orientation of the extraordinary axis** of the SLM, **display an image** (with the HDMI cable disconnected at the computer, the EDK SLM cycles through patterns), **and experimentally determine a *common orientation* for the polarizer and analyzer which is *closest* to completely *extinguishing* the image**. [You'd find the same result for $\beta = \theta = 90°$.]

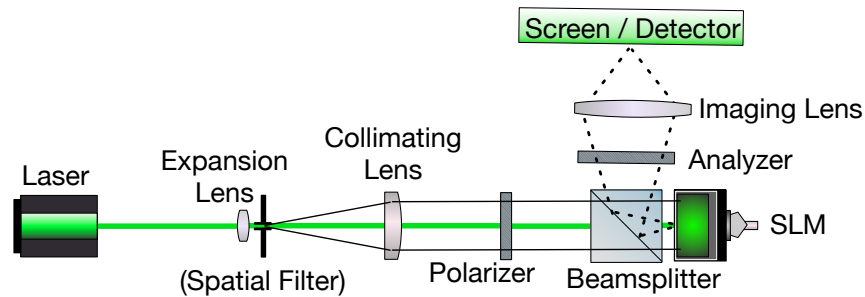One possible experimental setup is as shown in Fig. 3 below:



Fig. 3. Here, we expand the beam so that all of the SLM pixels are illuminated. If the illumination is markedly nonuniform, it may be necessary to complement the expansion lens with a *spatial filter*, which consists of the expansion lens plus a pinhole that can be placed at its focal point, blocking any skewed components of the input beam while allowing passage of the plane wave input component that is parallel to the optic axis. With the addition of an imaging lens, the screen position must be *adjusted* to bring any SLM-displayed image into sharp focus.

The position of the SLM defines the object plane of the Imaging Lens. The position of the Screen is adjusted such that the object distance, $o$, along the (folded) optic axis and the image distance, $i$, are (approximately) related to the focal length, $f$, of the imaging lens by the thin-lens equation:

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

In practice, you can simply move the screen to bring any SLM-displayed image into focus, …but recall that the [magnification](#) of the image depends on where the Imaging Lens is placed. ***Think!***

Discuss, with you lab partner, what these next steps *ought* to mean: after you have experimentally determined a *common orientation* for the polarizer and analyzer that completely *extinguishes* the image, carefully **record this angle**, as your experimental result for the orientation of the extraordinary axis of the SLM.

### *Step 2: Moving to Amplitude Modulation Mode*

Next, you need to make adjustments to the orientations of the polarizer and analyzer *relative* to the settings determined in Step 1, to achieve the conditions necessary for *Amplitude Modulation*: $\beta = 45°$ and $\theta = -45°$. This means that the angle between the input Polarizer and the output Analyzer is 90°, so **if the SLM *were* simply a mirror, the transmissivity should be zero**. On the other hand, **if the SLM were a Half-Wave Plate** (HWP), an input beam polarized at 45° with respect to its extraordinary axis would be output by the HWP with its polarization rotated by 90°, and so would not be blocked by the output analyzer, yielding a **predicted transmissivity of one**. Of course, the SLM is not simply a mirror, and it is not simply a HWP; it is a *variable retarder*. Evaluate Eqn. (1) for $\beta = 45°$ and $\theta = -45°$. **You will be using this prediction as a model, to *fit* your experimental data**. Ideally, you would also construct a clear mental model for what the (Polarizer + SLM + Analyzer) system is doing *as a function of* grayscale level. Record your thinking into your lab notebook.

At this point, any grayscale image displayed by the SLM is no longer extinguished, but should be clearly visible on your imaging screen:
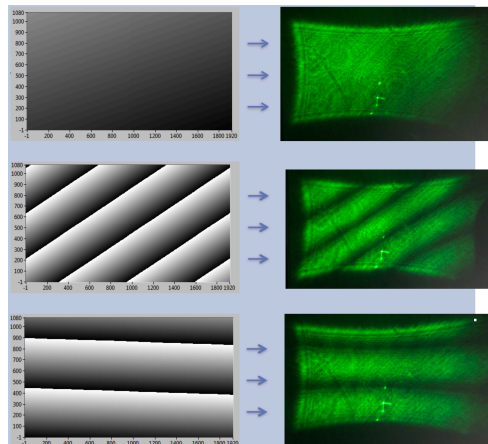


Fig. 2. Example input and output images in Amplitude-Modulation mode, taken by a student at Illinois Wesleyan University. Despite the presence of *pincushion distortion* in his output images, the results clearly demonstrate pixel-by-pixel control of amplitude.

Make sure your HDMI cable is connected, so that you can replace the image previously displayed on the SLM with a uniform screen, where all pixels are set to the same grayscale value, and **replace the imaging screen with a photometer**. — **Measure the power** for a wide variety of grayscale values, starting at 0 and ending at 255.

Plot your data, and ***fit it to your model***. Re-write your model in terms of a parameter that describes the apparent phase shift produced for each grayscale value applied. Your notebook must include your data (the graph, with your data points *visible*), the fit equation, and the parameter that describes the phase shift.

Consider the following *example* data taken at two different stations in our lab:



Fit function:
$y = C + A*\sin^2(B*x)$

When the SLM acts as a HWP
(meaning a phase shift of $\pi$)
we expect Max Transmissivity.
Hence, $\partial\Phi/\partial x = 2B$

SLM #2:
A = 7.5752 ± 0.278
B = 0.012433 ± 0.00015
C = 2.0812 ± 0.169

SLM #1:
A = 4.7178 ± 0.0976
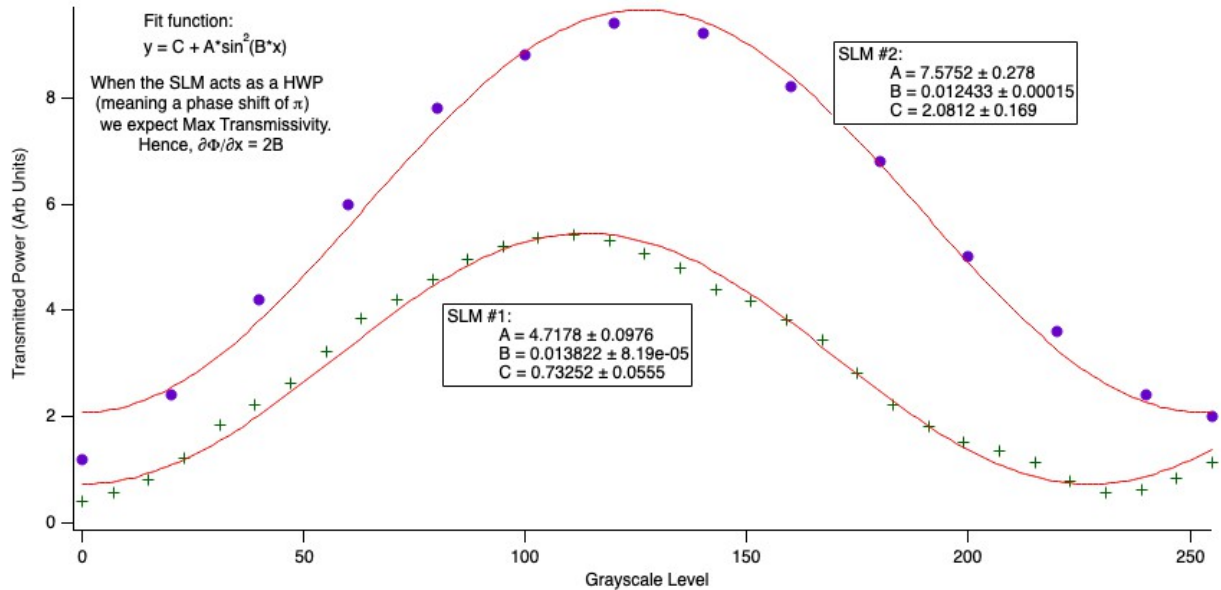B = 0.013822 ± 8.19e-05
C = 0.73252 ± 0.0555

Fig. 3. At two lab stations, the input polarizer was oriented so that it was not
aligned with either the ordinary or the extraordinary axes of the SLM, but
roughly halfway between those orientations. While the "grayscale" level of
every pixel of the SLM was set to zero, the output analyzer was turned so as to
minimize the transmissivity of the system. Images created by the IDL code
"pistonbatch" were sent to the SLM via a PowerPoint slideshow.

There is uncertainty associated with any one of your data points but, collectively, your data
points might give you some confidence in determining which particular grayscale value
corresponds to $2\pi$, for your *particular* SLM. Armed with that value, you can "rescale" any phase
profiles you might program (throughout this course), so be sure to record that result now!

At what grayscale level does your SLM act like a **quarter** waveplate (QWP), converting linearly
polarized light into circularly polarized light? How can you test this?

At what grayscale level does your SLM act like a **half** waveplate (HWP), rotating the
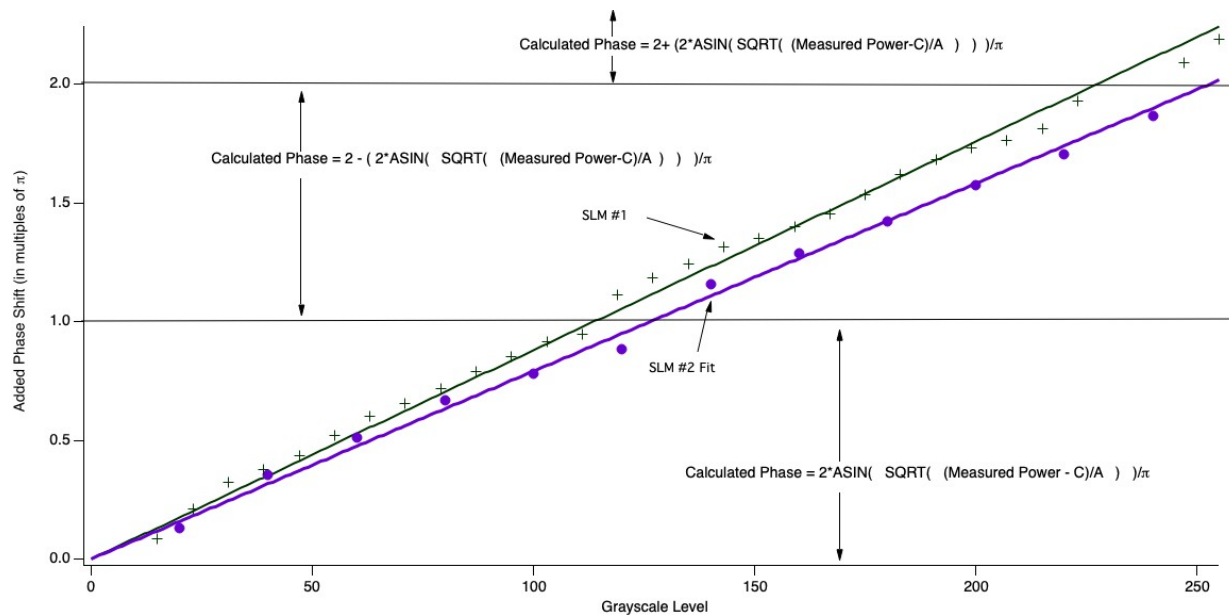polarization of linearly polarized light? How can you test this?

Fig. 4. For each particular SLM studied in Fig. 3, the ensemble of data points yielded a best-fit value for the parameter B. That parameter, on its own, determines the slope of the solid line shown above, which corresponds to the "average" added phase shift per increment in grayscale. In order to show how the individual data points compare to that average, I inverted the fitting equation from Fig. 3, to yield a predicted phase throw for the observed transmitted power at each grayscale level studied. For phase shifts greater than $\pi$, [I had to take into consideration the fact that calculators (and programs like *Igor Pro*) will report the results of inverse trig functions, by default, as being angles that reside in the first quadrant of the unit circle, exclusively!]

As you stepped through various grayscale levels, to build up your calibration curve, the output of the SLM traversed a *trajectory* on the [Poincaré Sphere](#) corresponding to a great circle. Does that trajectory ever yield an output that is polarized at 45°? Does it ever yield an output that is polarized at -45°?

## *Opportunities for Initiative:* (your own ideas may be better!)

1) The series of images created from your own "1st IDL program" assignment, can be sent to the SLM via a PowerPoint slideshow. Try it! — For that exercise, you will no longer need either the photometer or the lens that collects light onto that single-pixel detector. Instead, you are interested in observing the *spatial distribution* of intensity, far away from the aperture function that you've programmed, and how those observations change as you systematically vary your aperture function.

2) You should now be able to configure your SLM to toggle between acting as a waveplate with retardances of 0, $\pm\lambda/4$, $\pm\lambda/2$, 1.

3) Try Part 2 of your reading on [Alignment](#). Try Part 4 of your reading on [Alignment](#).