Name: ______________________
Partner(s): ______________________
Date: ______________________

Independent **Calibration, in *Phase*-Modulation Mode**

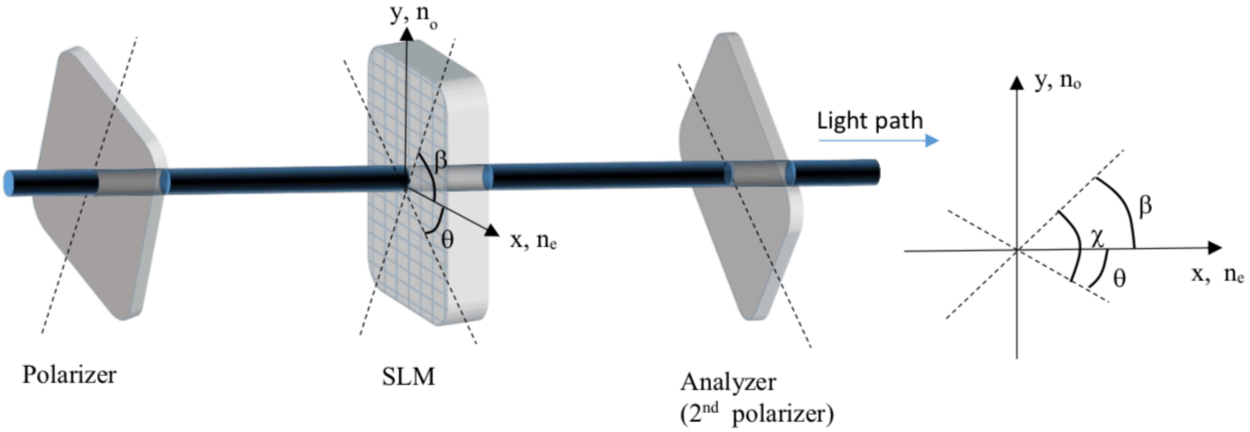


Fig. 1. In this **Polarizer + SLM + Analyzer** schematic, the *x*- and *y*-axes are fixed by the SLM orientation, which differs *significantly* from the horizontal and vertical directions in the lab. [Fig. credit: Lowell McCann, UW-River Falls]

You have predicted the transmissivity of a **Polarizer + SLM + Analyzer** system to be:

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

By judicious orientations of the polarizer, on the input and the analyzer, on the output, we select the *kinds* of adaptive control that the SLM will have upon the beam (*e.g.*, local control over the *amplitude* of the output beam, or local control over the *phase* of the output beam, or some combination of the two). — The last lab focused primarily upon "Case A:" Amplitude Modulation of local areas within a laser beam, and used this to calibrate the phase shift imparted by the SLM, for each applied grayscale value. Today, you perform a second, independent set of measurements aimed at calibrating your SLM. Write, in your lab notebook, thoughts about why such an exercise might be a good idea.

How can you achieve "Case B:" Phase-only modulation? In Step 1 of your previous lab, you recorded, in your lab notebook, your experimental result which you took to be the orientation of the extraordinary axis of the SLM. When the input polarizer and output analyzer are aligned along this orientation, you found that images sent to the SLM cause no amplitude modulation. That is possible only when $\beta = \theta = 0°$, *or* when $\beta = \theta = 90°$. One of those will allow phase modulation. The other orientation allows for no modulation whatsoever. *Why?*

Calibration of *femtosecond-level time lags* encoded into local regions of a beam

As the phase shifts imposed by the SLM amount to extraordinarily small *time delays*, we would be hard pressed to detect these *directly*. **Our eyes detect intensity, and not phase**, so to sense (and *calibrate*) any phase changes encoded into the output beam, we will need to *interfere* the output of the SLM with a *reference* beam, here provided by a mirror added at the bottom of the schematic below:

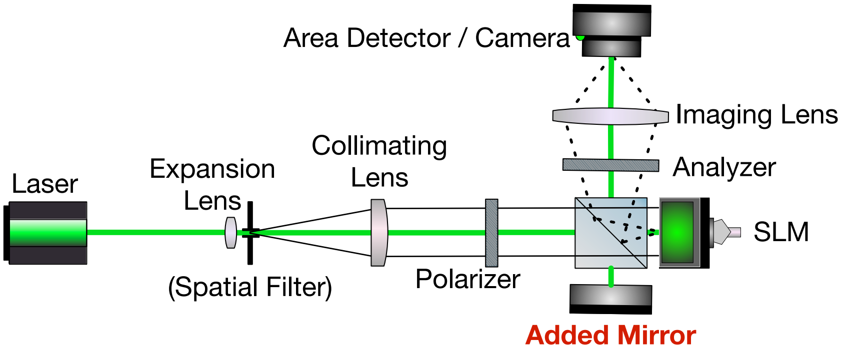


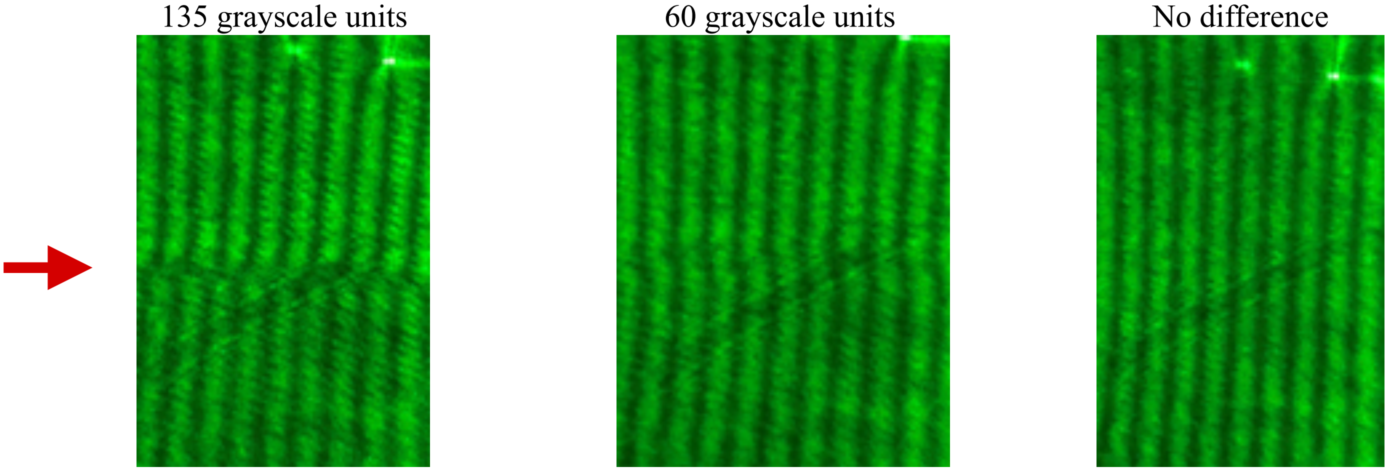
Fig. 2. Here, the image produced at the Area Detector / Camera will be an *interference pattern*, generated by the combination of light reflected from the SLM and light reflected from the newly added mirror.

CAUTION avoid detector saturation!

The reference mirror and the SLM are *equidistant* from the beam splitter, to within the coherence length of the laser, otherwise no **interference pattern** can be observed. It may be necessary to replace the expansion lens with a spatial filter, which consists of an 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.

Display a pattern on the SLM where one side is completely black (grayscale = 0) and the other side can be stepped from black to white (from 0 to 255). (A constant offset phase factor added to one arm of an interferometer is often referred to as “piston” or “bias,” and is equivalent to changing an optical path length.) If you have aligned the input polarizer with the extraordinary axis of the SLM, changes in grayscale level will no longer cause any changes to the *polarization state* of the reflected beam, but will instead *only* affect the effective optical path length traversed. Recall that, because the wavelength inside the medium will be reduced from its value in air, $\lambda = \lambda_0/n_e$, these grayscale values will *tune* the degree to which different parts of the beam (coming from differently addressed SLM regions) will emerge *in phase*. For calibration of these phase shifts, a **reference zone** on the SLM is kept at a fixed applied voltage, while the voltage applied to a **test zone** is incrementally advanced through the 256 allowed “grayscale levels.”

Phase difference between top and bottom halves:



135 grayscale units

60 grayscale units

No difference

Fig. 3. In the sample data shown above, the arrow at left points to the fact that the observed fringes coming from the top half of the SLM are clearly displaced, relative to those coming from the bottom half. (In this particular data set, the two patterns out of phase by π when the difference in grayscale levels is $\sim$ 135.)

Make tip/tilt adjustments to the mirror so that you create a set of horizontal interference fringes on the camera. There should be a region of at least 5 sets of *uniformly spaced* fringes, but not more than 30.

Analyze the displacement of the *fringes* associated with your test zone on the SLM, relative to those associated with your reference zone:

Example Method #1: "Quick 'n Dirty" (**recommended**)

First, using whatever tool seems simplest, find the "distance" from one bright fringe to the next in units of pixels in the reference zone image: this corresponds to a 2π phase shift. [Note: it is usually better to measure across multiple periods and then calculate the average, to get a more accurate value.]

For each grayscale setting applied to your test zone of the SLM, using whatever tool seems simplest, measure the distance that the fringes *shift* from their original position. Using the period value found above, convert this to the equivalent *phase* shift.

Make a plot of phase shift *vs*. grayscale value. Analyze, and comment upon, your results.

Example Method #2: Enhanced Statistical Averaging (**initiative**)

Here's a sample *Mathematica* notebook, introducing some methods for image processing and image analysis. I call it "Fringe Science." Previous student groups in this course have each used a different method for analyzing their images. In every case, their methods were much simpler than what's outlined in my ("Fringe Science") *Mathematica* notebook!

Questions:

We model the beam coming from a zone of the SLM and the reference beam coming from the Mirror to be two coherent plane waves that cross at an angle θ. The resulting interference pattern can be found by adding the *fields*, and then squaring to find the intensity or irradiance. We make use of a trig identity:

$$\cos^2\theta = \frac{1}{2}(1 + \cos 2\theta)$$

Then, we predict that the harmonically varying fringes can be described by:

$$I = 2I_0\left[1 + \cos\left(2k_x x\right)\right] = 2I_0\left\{1 + \cos\left[2\left(k\sin\frac{\theta}{2}\right)x\right]\right\}$$

where x is the distance across the interference pattern. This much is formally treated in *Optics f2f* Section 3.3 but to describe this week's experiment we must include a controllable constant offset ("piston" or "bias") phase shift, ϕ, added to one of the interfering beams, yielding this model:

$$\boxed{I = 2I_0\left\{1 + \cos\left[2\left(k\sin\frac{\theta}{2}\right)x + \phi\right]\right\}}$$

Your analysis should be aimed at determining the added phase shift, ϕ, over the available range of grayscale values that can be applied to the SLM.

In this way, you have performed a second (independent) set of measurements aimed at calibrating your SLM. Write, in your lab notebook, your thoughts about any comparisons you might make between your results from this week and your results from last week (physical causes of any difference, which method might be more accurate or precise, the degree of confidence you now have in your knowledge of AND uncertainty in the nominal phase throw produced by each grayscale value applied, *etc*.

Opportunity for Initiative: (your own ideas may be better!)

The calibrations performed here implicitly assume both that the SLM and the Added Mirror are optically "flat," and that the input beam is a plane wave, free of any kind of aberration. It turns out, given that you have plenty of laser light available, that you can determine an experimental correction for *any* aberrations in this (or any) optical system, if you divide the SLM into *smaller zones*. Suppose, for example, that you define a zone with each side containing, say, one eighth of number of pixels of the SLM. The full SLM would then consist of 64 such zones, one of which you might fix as the **reference zone** on the SLM. Essentially, all you would need to do is to repeat the calibration for each of the remaining 63 test zones, and you would then know of (and be able to compensate for) any offset phase shifts between zones.

When we say that you can experimentally correct for *any* aberrations, this statement carries some constraints. For example, you can only use the approach described above to correct for aberrations that vary with time on a scale that is slower than the time it takes you to work out the correction. Moreover the correction attains higher a fidelity if you can take the time to divide the SLM into a larger number of zones. Still, it is true that the correction compensates for aberrations that might be due to misalignments that come either before or after the SLM in your optical system. The phase pattern you impart with the SLM is *additive* to whatever phase profile already exists in the beam, and this approach to aberration correction is feeding off of the detected output at some final camera, which also includes whatever phase changes might occur *after* the SLM, from lenses or other optical components.

As initiative, you might simply *read* (and comment upon, in your lab notebook) a paper introducing this kind of approach to aberration correction, which we've dubbed "Spot-Optimized Phase-Stepping" (published by some of our collaborators in *Nature Photonics*). [And, if you wish, you could read our own follow-up paper, aimed at extending this approach.]

You might even want to enter into further discussion about such methods, and the opportunities that exist for creating your own (publishable) extensions!

Towards computer-controlled holograms:

Clearly, the SLM can provide pixel-by-pixel programmatic control over the **phase** of the transmitted light, which will serve as the basis of our future work on Computer-Generated *Holograms*. As noted above, phase control of this sort can also provide a *dynamically adjustable* means of correcting for aberrations in any optical system you might ever build. Next week, we will demonstrate how phase control allows you re-shape wavefronts in conceptually useful ways.