Name: ____________________________
Partner(s): ____________________________
Date: ____________________________

Digital Optics: ***Pixels*** as a Platform

Objectives: (first **3** pages are for *class*; next **3** pages are our *lab*)

- To introduce the notion of "*diffraction noise*," arising from the periodic structure of *most* pixelated devices (eyes, for what it's worth, are also pixelated devices, albeit ones which may contain a "disordered hyperuniform" array of pixels).
- To consider the possible *percentage* of input light that can be controlled when using a pixelated device, by measuring the "*filling fraction*" of multiple devices. These examinations extend to inexpensive Digital Micro-mirror Devices (DMDs), to transmissive "Spatial Light Modulators" (SLMs) that we can take from classroom projectors, and (very quickly) onwards to (much more useful) reflective SLMs. Because SLMs allow simple programmatic control of phase and/or amplitude (or polarization) within many local regions across the field of a beam of light, they serve as tools for direct exploration of mathematical models contained in the text.
- To further expand our mental *models* of Digital Optics devices.

In-class Background:

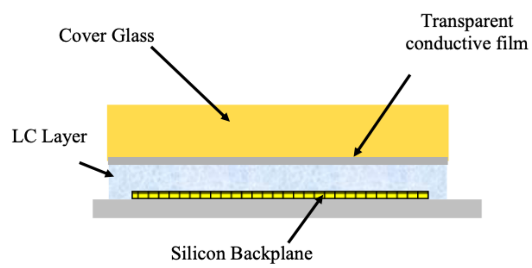


Fig. 1. Digital optics devices, such as the reflective Liquid Crystal-on-Silicon (LCoS) above (Meadowlark Optics) are based upon an array of independently addressable "pixels." Unfortunately, *even when the device is turned off*, this pixelation means that output light will be structured, in a manner that depends upon diffraction, due to the size of each pixel, and interference, which depends upon the periodic spacing between pixels. The resulting structure in the output beam is sometimes referred to as "**diffraction noise**."

For this week's lab, we take a break from introducing the uses of *mathematical* matrices in Optics (though we will be returning to and extending that much more, later on), and instead consider the fact that Digital Optics devices consist of *physical* matrices. (No, not the place where you might encounter a character named Neo.)

Design choices (and limitations):

Given the easy availability of 3D printers on campus, you may wish to design your own *phased array* (*i.e.*, an array of source elements, or "pixels," where you can programmatically adjust the relative phases of the output beam, on a pixel-by-pixel level). The easiest phased array to make consists of *acoustic* sources. Unlike the transverse waves of light, the longitudinal waves of sound moving through air have *no polarization*. On the other hand, diffraction and interference effects occur with *any* type of wave, so these arrays will still be subject to "diffraction noise" of the sort identified in Fig. 1. Clearly, coherent sound waves, like coherent light waves, can interfere with each other to form more complex patterns, meaning that you can form acoustic *holograms* by interfering multiple sonic sources of identical frequency and tailored phase.

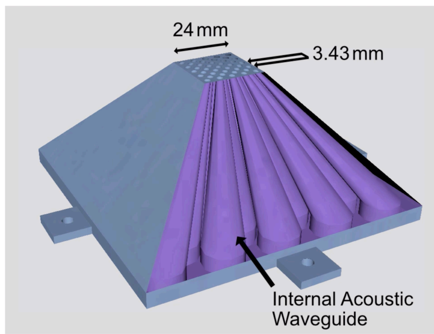


Fig. 2. To eliminate the undesired "**grating lobes**" that arise when using a periodic array of sources (due to diffraction and interference), for our ***acoustic*** holograms, we can use a 3D-printed *tapered waveguide* that reduces the effective separation between transducers to the point where first-order lobes are moved "beyond the horizon." Such an approach is *not* possible with light.

With diffraction and interference, recall that what is "small" in the plane of the diffracting object becomes "big" on an imaging screen (or detector array) placed very far away from the object. For example, in PHYS 106 students shine a laser onto a periodic array of apertures, and find that for a *smaller* spacing between the apertures, diffraction minima will be moved out to *higher* angles. So, when we designed the Digital Acoustic phased array described in Fig. 2 we made sure that the spacing between pixels was reduced to less than half the wavelength, so that the first-order diffraction minima would remain beyond the horizon even as we tailor the relative phase between sources.

At first you might think that we should design Digital Optics devices the same way: just keep making smaller pixels! However, your experiments on polarization prove that **optical waves are *transverse* waves**. This means that the "modes" supported by an optical waveguide are a lot like the "particle-in-a-box" solutions you encountered in Modern Physics. Once the diameter of a waveguide is reduced to be smaller than a half wavelength, there are simply no modes supported and so the waveguide is said to have been driven "beyond cutoff," which means there is no transmission to "far field" (where your imaging screen or detector array placed). [Some of our previous students made arrays of sub-wavelength optical apertures, *which are available to you*.]

In lab, you will analyze light diffracting from various Digital Optics devices, to find the size, *d*, of each discrete pixel and the *period of pixel spacing*, *D*, illustrated, in cross-section, in Fig. 3, and then calculate the *fraction* of the device area that you can programmatically control.

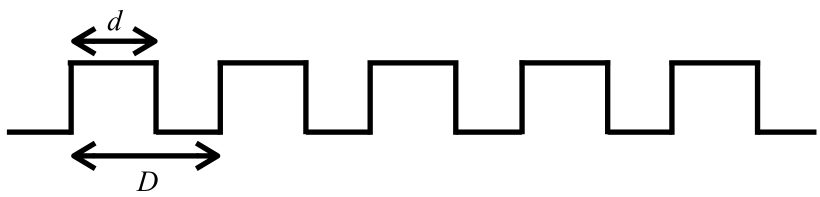


Fig. 3. In cross-section, Digital Optics devices have a periodic aperture structure.

From Pedrotti & Pedrotti's *Introduction to Optics* (Eqn 16-32, 2nd Ed.), a 1-dimensional periodic array of *N* slits, yields the following model for the irradiance of diffracted light:

$$I = I_0 \left(\frac{\sin \beta}{\beta} \right)^2 \left[\frac{\sin(N\alpha)}{\sin \alpha} \right]^2 \quad (1)$$

In Eqn. (1) above, the first term in parentheses describes the intensity profile due to a *single* slit, which provides an *envelope function* modulating the amplitude of the *N*-slit interference pattern described by the last term. Here ***d*, the slit width**, is contained within $\beta = (1/2)kd \sin \theta$, where θ is the angle of the diffracted light, measured from the normal to the SLM surface, and $k = 2\pi/\lambda$ is the wave vector magnitude and ***D*, the slit separation**, is contained within $\alpha = (1/2)kD \sin \theta$. [Later in the course, we will endeavor to *show* this result.]

When you are illuminating a large enough number of apertures, the final term creates very sharply defined bright spots. That is, when *N* is large enough, the only angles displaying significant intensities will be those which correspond to the final term reaching its maximum value (of one). From the formula for α, you can immediately see that these bright spots will occur at a set of angles, denoted θ_{maxima}, where:

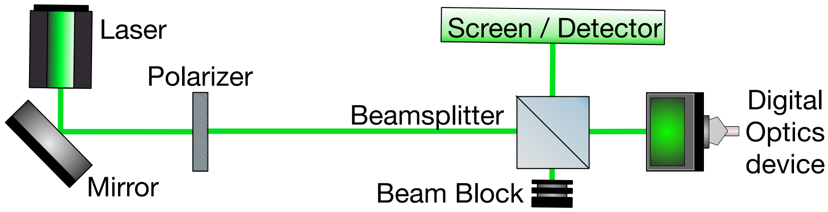
$$D \sin\left(\theta_{\text{maxima}}\right) = m\lambda, \text{ where } m \text{ is an integer.} \quad (2)$$

This is an equation that should look *familiar* from your Introductory Physics coursework!

Of course, these bright spots will not all have equal intensity, because their relative intensities are modulated by the (familiar) single-slit envelope function, $\left[\sin\left(\beta\right)/\beta\right]^2$. Evaluating this envelope function at the angles of maxima determined by Eqn. (2), we find the relative intensities to be:

$$\left(\frac{\sin \beta}{\beta} \right)^2 = \left[\frac{\sin\left(\pi m \frac{d}{D}\right)}{\pi m \frac{d}{D}} \right]^2 \quad (3)$$

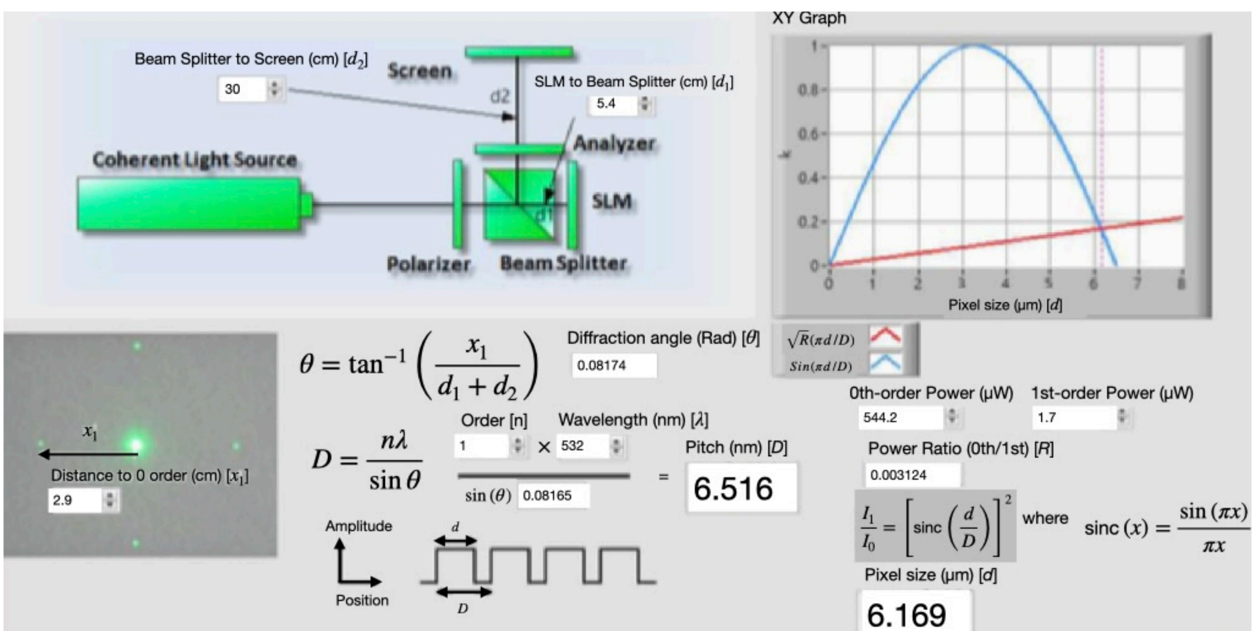
Fig. 4. One possible experimental setup. **You may prefer a simpler approach.**



(For the rest of the course, alignment mirrors and beam blocks will *not* be explicitly shown, but you should always assume their necessity.)

Avoid saturating any detector or camera that you may use!

By measuring the **locations** of the 0th-order and 1st-order intensity maxima, you should be able to determine D, the *period of pixel spacing* on the Digital Optics device being studied, by using Eqn (2) above. Then, by measuring the ***relative intensities*** of those two diffraction orders, you can determine the ratio d/D, from which you can calculate both the *pixel size*, d. The ratio d^2/D^2 tells you the *fraction* of the device area that you will be able to programmatically control, and is referred to as the "***filling fraction***" of that device. Your methods for measurement and analysis should be clearly described in your lab notebook.



Our green lasers have a wavelength of approximately 532nm. If you opt to use a laser whose wavelength is *not* known, you can find it by using the manufacturer's specifications for the Jasper EDK SLM: D = 6.5 µm, d/D = 0.97. Once that is known, you can then use your experimentally determined wavelength to find the (unknown) geometry (*e.g.*, pixel size and *pitch*) and filling fraction of other Digital Optics devices available in the lab. For any device you measure, make note of the *ratio* of the pixel size compared to the wavelength of the light used.

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

Investigate an SLM device claiming "no diffraction noise"

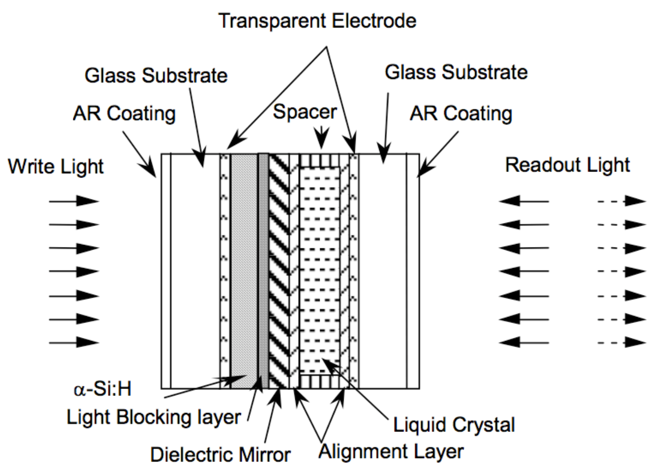


Fig. 5. The Hamamatsu x8267 SLM is not directly electrically *addressed*; rather, while there is a voltage applied between the front and back transparent electrodes, the device is *optically* addressed, by a micro-LED array called the "write light." Where no write light is incident the $\alpha -$ Si:H (amorphous silicon) layer has extremely high impedance, but the impedance of the amorphous silicon decreases, roughly in proportion to the logarithm of the write-light intensity, and so the voltage applied across the liquid crystal layer increases according to the intensity of the write light.

Hamamatsu was able to produce a model, the x8267 SLM, with a notably unique design, illustrated in Fig. 5: there is **no *physical* pixelation** of either the liquid crystal solution or of the reflective backplane, which is "optically addressed" via illumination of a semiconductor by a micro-LED array that sits behind the device.

Make a test pattern for the Hamamatsu "optically addressed", that alternates, at a pixel-by-pixel level, between grayscale values of zero and 128. Then, with the device powered on, repeat your diffraction experiment for this novel device.

Another manufacturer, HoloEye, defines their SLM design specs as follows:

- **Resolution:** Number of pixels (width × height)
- **Pixel Pitch:** Size of a pixel *including* the inter-pixel gap
- **Fill Factor:** Surface area of the display which can actively used. There are gaps between the pixels at which the incident light is scattered.
- **Active Area:** Size of the actual addressable/usable display area.

- **Addressing:** Number of gray levels / phase levels that can be addressed. This can vary with addressing sequences.
- **Signal Formats:** Input signal format. Typically HDMI or DVI.
- **Input Frame Rate:** Addressing speed of the input signal (*typically* DVI / HDMI video frame rates of 60 Hz for monochrome applications).
- **Response Time:** The response time is defined as the switching time from 10% to 90% and from 90% to 10 % (rise and fall time). The actual response time of the liquid crystal is determined by the properties of the used liquid crystal material, the thickness of the LC layer, the used drive sequence / calibration (the actual voltages applied to a pixel) and *temperature*. Note: for phase-modulation SLMs the response time typically is *below* the Input frame rate.
- **Reflectivity:** Amount of light which is directly reflected (0-order of a non-addressed display). The reflectivity is not 100% as some of the light is diffracted into higher orders due to the grating like structure of the pixel matrix. Some part of the light is also scattered and absorbed at the inter-pixel gaps. In addition the reflectivity of the electrode mirrors is limited (dependent on wavelength).
- **Damage Threshold**: Except when using low-power beams, the incident light should be expanded to fill the active area. Too much power in one spot will boil the liquid crystal solution, *irreversibly* damaging the device.

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Acoustic Phased Arrays:

We've used simple open-source CAD software, *OpenSCAD*, for the design in Fig. 2: a tapered array of acoustic waveguides, with matching base. Either use the links provided to modify it, or use our design *as is*, for 3D printing. (As tolerances vary from one 3D printer to the next, a wise use of your time might be to *test print* one hole, rather than an entire array, to make sure that the available transducers actually fit.) A MakeBlock XY-Plotter Robot Kit v 2.0 is available in the lab, to scan a detector across the output, thereby mapping out any acoustic holograms generated.
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Self-Assembling Nanosphere Lithography for generation of Sub-Wavelength Optical Apertures:

If interested, chat with your instructor about novel methods to extend recently (2019) developed methods for generating (and using) sub-wavelength optical apertures.
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Discuss other pixel-based technologies with your instructor!