A low-cost spatial light modulator for use in undergraduate and graduate optics labs

Derek Huang, Henry Timmers, Adam Roberts, Niranjan Shivaram, and Arvinder S. Sandhu[a)]
Department of Physics, University of Arizona, Tucson, Arizona 85721

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Spatial light modulators (SLMs) are a versatile tool for teaching optics, but the cost associated with an SLM setup prevents its adoption in many undergraduate and graduate optics labs. We describe a simple method for creating a low-cost SLM by extracting components from a commercial LCD projector. We demonstrate the pedagogical applications of this SLM design by providing examples of its use in teaching diffraction and interference phenomena. We also discuss an SLM's potential as a research tool in graduate labs. In particular, we demonstrate its use in holography and in the generation of optical vortices.
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I. INTRODUCTION

Spatial light modulators (SLMs) are opto-electronic devices that modulate the amplitude or phase of a beam of light. SLMs have been used extensively in various research fields, including ultrafast pulse shaping,[1] optical computing,[2,3] and microscopic laser surgery,[4] and are used in a number of other applications where one desires to manipulate the spatial profile of a light beam.

Using an SLM, one can demonstrate the concepts of diffraction, interference, and holography in a dynamic fashion with real-time control over the parameters. In addition, SLMs make possible new experiments that are not accessible with standard lab equipment. Thus, incorporating an SLM into optics laboratories would not only introduce students to a vital tool of contemporary research but it would also allow a more hands-on approach to teaching traditional topics such as diffraction and Fourier optics. Unfortunately, SLMs from laboratory suppliers typically cost several thousand dollars, making them prohibitively expensive for pedagogical purposes. In this paper, we describe a cost-effective method for creating an SLM by extracting components from a used commercial LCD projector that costs around \$150. We then demonstrate this SLM's capabilities as an addressable diffractive element for use in undergraduate laboratories.

The most common type of SLM is the liquid crystal display (LCD), which incorporates a pixelated layer of polarization-altering liquid crystals between two polarizers in order to modulate the intensity of the transmitted light. A simple sketch of an LCD-SLM pixel is shown in Fig. 1(a). The input beam is polarized horizontally before entering the liquid crystal assembly. The polarization can then be rotated depending on the voltage applied across the pixel. The analyzer on the output side transmits only the vertical component of light. The voltage applied to each pixel thus controls the intensity of transmitted light. Because the liquid crystal SLM matrix can be easily controlled by a computer, this scheme allows real-time manipulation of the wavefront of a light beam by creating amplitude and phase masks on-demand.

Demonstrations of diffraction and interference phenomena with static masks are a key element of undergraduate optics labs. However, the diffractive elements used in these labs are usually limited to simple, readily available masks such as line gratings, double slits, etc. The exploration of more complicated diffraction effects would be a valuable educational tool. Unfortunately, the creation of custom diffractive elements involves either a time-consuming process or costly purchases from a laboratory supplier. Furthermore, static diffractive elements do not easily allow for modification, thus limiting their utility. In contrast, a computer-controlled SLM would allow students to design their own diffraction elements in an attempt to produce interesting interference patterns, and also to change the masks in response to an experimental result.

Beyond pedagogical applications, we discuss applications of the SLM in many areas of current research, such as phase shaping, optical tweezers, laser mode conversion, and optical vortices. Some of these applications can also be incorporated into graduate research projects. In particular, we focus on the generation of optical vortices. With the proper holographic diffraction mask, an SLM can create an optical vortex, a beam that is twisted like a corkscrew around its axis of propagation, such that its phase varies azimuthally from 0 to 2π.[5,6] At the center of the optical vortex, the phase is undefined, resulting in a dark spot called a phase singularity. The twisted structure of an optical vortex imbues each photon with an orbital angular momentum (OAM).[7]

The rest of this paper is organized as follows. In Sec. II, we describe the procedure for creating the SLM and the experimental setup. Section III describes how the SLM can be incorporated in the diffraction and interference experiments for undergraduate laboratories. Finally, in Sec. IV, we consider applications of the SLM suitable for graduate level experiments, such as the generation of optical vortices.

II. PROCEDURE AND EXPERIMENTAL SETUP

The SLM was created by modifying a used Infocus LP1000 LCD projector, which we purchased on eBay for \$150. This projector uses three SONY LCX017AL LCD panels to modulate the RGB values of white light. The transmission efficiency of the LCD is 21% and it has a resolution of 1024×768 pixels, with a pixel pitch of $39.1\ \mu m \times 35.9\ \mu m$ and an active area of $4.00\ cm \times 2.76\ cm$. Each pixel consists of a thin-film transistor and a series of twisted-nematic crystals. Light that enters the LCD passes through a polarizer called the director. A second polarizer, called the analyzer, is placed after the liquid crystals with an axis orthogonal to the director (Fig. 1(a)). When the transistor is addressed with an OFF voltage signal, there is no electric field in the liquid crystal layer so the liquid crystals remain in a helical shape. Light that enters is initially polarized along the axis of the director and then rotated 90° by the twisted liquid crystals; this leaves the light aligned with the analyzer and allows it to pass through. When the transistor is instead addressed with an ON voltage signal, an electric field is generated in the liquid crystal layer causing the crystals to orient along the axis of the director. The polarization of the light remains unchanged as it passes through the liquid crystal and is therefore blocked by the analyzer (Fig. 1(b)). Intermediate voltage signals lead to partial transmission of light. In this way, the LCD modulates the amplitude of incident light through each pixel. This amplitude modulation can be used to create on-demand masks and diffraction elements. We note that phase-only modulation[8] has been reported to yield greater diffraction efficiency. However, for the purposes of this paper, we use the simpler amplitude modulation setup, though we consider the possibility of phase-only modulation in Sec. IV.

To turn the LCD projector into an SLM, it is best to remove the casing, optics, fans, speakers, and lamp, leaving only the power source, lamp ballast (the component that the lamp connects to), LCD panels, the main circuit board, and the small control panel that attaches to the main board. Much of the disassembly process is a matter of unscrewing and removing parts that have been attached with epoxy. The layout of various components is shown in Fig. 2. The projector has safety interlocks preventing it from functioning if the casing, fans, or lamp are not detected. The casing interlock is a simple switch on the power supply that needs to be depressed for the projector to turn on. After the casing is removed this switch can be permanently tied down to defeat the interlock. The fans should be replaced with resistors of similar resistance. The lamp itself can be easily removed, but without a working lamp attached, the projector will power up but not function. To restore functionality, the correct voltage signals must be sent to the circuit board. A 16-pin connector, shown on the right panel of Fig. 2, links the circuit board to the lamp ballast. The lamp ballast communicates the operational status of the lamp by sending appropriate voltage signals on specific terminals of the 16-pin connector. Terminals A and B read 0 V when there is no lamp and 5 V when the lamp is connected and functioning. Pin C is always at 5 V. Using Pin C to provide a constant 5 V signal to terminals A and B allows us to communicate a false "OK" signal to the circuit board. With interlock thus defeated, the SLM can now be used with the lamp removed.

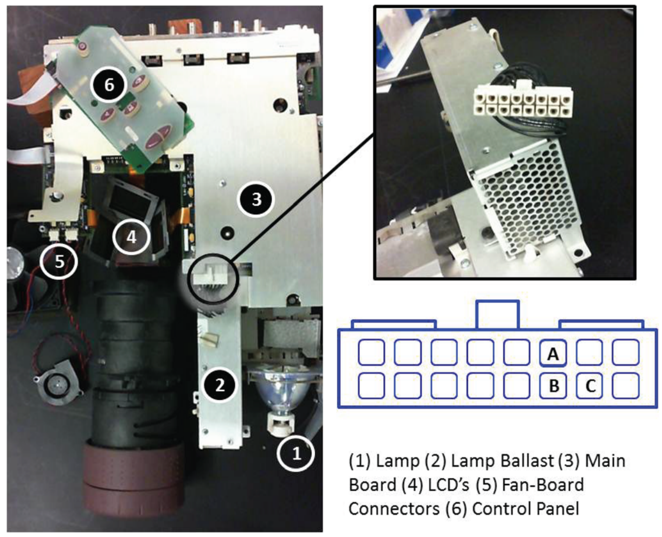

Fig. 2. (Left) Partially disassembled LCD projector. (Right) The 16-pin connector that communicates the status of the lamp to the main board. Pins A and B receive 5 V signals when the lamp is functioning while Pin C is continually 5 V. Soldering A, B, and C together defeats the lamp interlock.

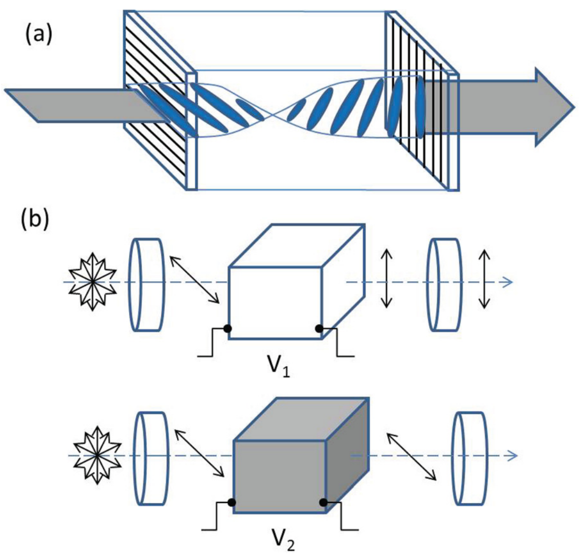

Fig. 1. (a) Operation of an LCD pixel showing the polarizers that act as the director and analyzer. Rotation of the polarization depends on the voltage across applied to the LCD. (b) The transmissive and opaque states of an LCD pixel.

There are three LCD panels attached by short ribbon cables to the main circuit board. Though it is possible to use the LCD panels in this configuration, it is more convenient to extend the ribbon cable using 32 pin, male-to-male FFC jumper cables with a wire pitch of 0.5 mm. To make the extension, one end of the jumper cable must be clamped to the LCD ribbon cable so the pins on both ends are properly aligned. Epoxy can then be applied to fasten the two ends together.

On one side of the LCD there is a polarizing film and transparent plastic sheet adhered onto the glass. This polarizer acts as the analyzer for the LCD; the director is attached to a lens inside the projector. The polarizer and transparent sheets are of low optical quality and may even be burned by a strong laser beam, so it is advisable to remove them. Once the LCD is removed from its plastic casing, both the polarizer and transparent sheets can be carefully peeled away and the adhesive cleaned off with methanol.

In our setup, we mounted the circuit board driving the LCD components in a metal box so that it stands vertically and occupies less table space. The LCD being used for beam shaping was mounted on a mirror mount at an angle so the polarization of the incoming light is aligned with the director axis of the LCD. As shown in Fig. 3, we place one polarizer before the LCD, and a second, orthogonal polarizer after the LCD. The light source utilized in our experiments is a 532 nm, 10–100 mW continuous-wave (CW) laser beam. Before the beam reaches the first polarizer, it is enlarged by a telescope so that the beam diameter is 1 cm. Although spatial resolution should increase by further enlarging the

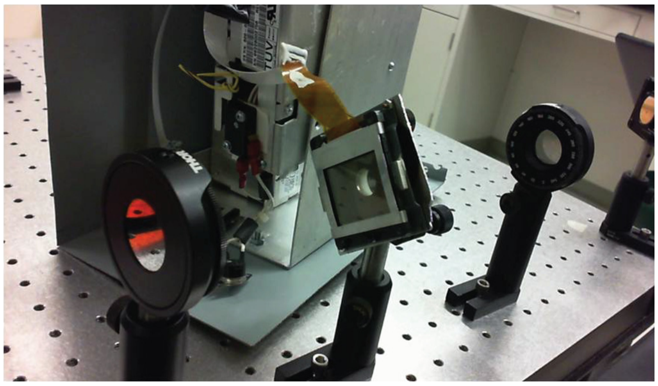

Fig. 3. A working SLM setup showing the control box and LCD element attached by a ribbon cable. Also shown are the polarizers that form the director and analyzer combination.

beam (thus covering more pixels in the LCD), we found that aberrations in the far field begin to occur for larger beam diameters.

Comparing our SLM setup to similar commercial products (e.g., Holoeye Inc., Model LC2002), we find that in terms of resolution, pixel pitch, screen size, refresh rate, and computer connectivity, the commercial version is very similar to our SLM. However, the commercial versions offer better contrast ratio, LCD quality, and aesthetics.

III. UNDERGRADUATE EXPERIMENTS IN DIFFRACTION AND INTERFERENCE

The versatility of the SLM makes it ideal for teaching diffraction theory. In the Fraunhofer plane, the observed interference pattern is related to the diffraction mask by the Fourier transform. To explore this relationship, students can design a diffraction mask on the computer using a program such as MATLAB. Then, using a 2D Fast Fourier Transform (FFT) function (such as Matlab's fft2) they can simulate the expected diffraction pattern. After displaying the diffraction mask on the SLM, students then observe the actual diffraction pattern and can compare the experimental and simulated images. As an example, Fig. 4 shows an example of a circular grating mask, the Fourier Transform of this mask, and the actual diffraction pattern observed when the mask is displayed in the SLM. For better visibility of the weak diffraction orders, logarithmic scaling is used on the simulated image.

It should be noted that even when the LCD is not displaying a mask, the transmitted light diffracts into a two-dimensional grid pattern due to the pixelization of the LCD. When a diffraction mask is displayed by the LCD, each of these pixel orders exhibits its own replica of the diffracted interference pattern. This can be seen in Fig. 4(d), which shows the full experimental image displaying multiple diffraction patterns that result from the discrete nature of the LCD pixels. A good exercise for students is to calculate the pixel pitch of the LCD by measuring the distance between two pixel orders and the distance from the LCD to the interference pattern.

The ability to display any mask pattern introduces an interesting twist to the standard optics labs. For example, instead of using a single- or double-slit aperture, one can easily make an aperture in the shape of the letter "A". As shown in Fig. 5, the match between the experimental and simulated diffraction patterns is very good in these demonstrations.

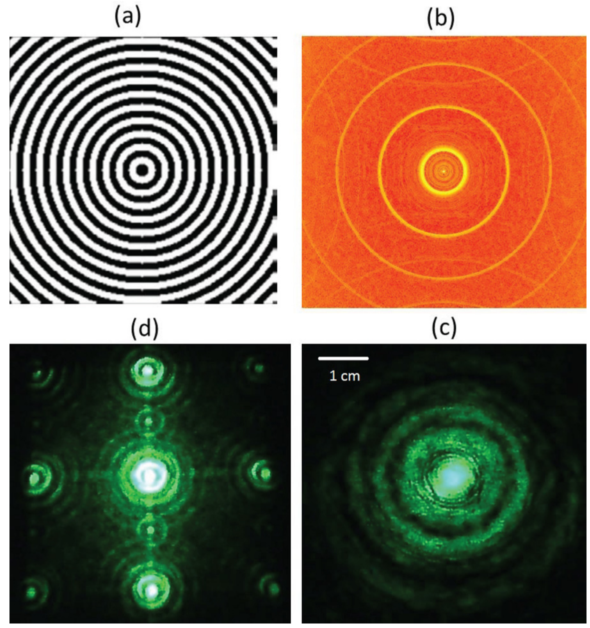

Fig. 4. A circular image mask example. (a) Image of a circular grating pattern, (b) the FFT of the image, and (c) the experimental diffraction pattern. The image plane is approximately 2.2 m from the SLM. (d) The full image showing multiple diffraction orders that result from the pixelization of the LCD.

In addition to static images, one can utilize an SLM to introduce dynamics into the study of diffraction or interference phenomena. In the simplest example, displaying a rapid sequence of double-slit masks on the SLM, with the distance between slits changing as a function of time, one can easily convey the dependence of the interference pattern on slit spacing. Such easy-to-construct dynamic examples, when incorporated into classroom demonstrations, can truly enrich the learning experience.

Another extension is to use an SLM to model x-ray diffraction from crystalline structures. Because the SLM enables easy experimentation with different two-dimensional structures, one can investigate the dependence of crystal diffraction orders on various lattice constants. This is demonstrated in Fig. 6, which shows the observed diffraction patterns from (a) a simulated hexagonal honeycomb lattice, and (b) a model of AlPdMn alloy's crystalline structure.[9]

IV. GRADUATE EXPERIMENTS: HOLOGRAPHY AND OPTICAL VORTICES

Apart from being a very useful pedagogical tool, SLMs also represents a sophisticated tool for graduate-level research projects. A number of active research areas can benefit from the use of SLM techniques. For example, control over a beam's spatial profile can play a crucial role in manipulating microscopic objects with optical tweezers.[10] In addition, phase shaping,[8] holography, and the generation of unique laser modes[11,12] (e.g., Bessel modes) can be implemented as a graduate-level exercise in optics. SLMs can also be used to generate Fresnel zone plates for imaging purposes.[13]

Perhaps the broadest use of SLMs in current research is with the creation of computer generated holograms (CGH). A hologram is created by recording the interference pattern of an object beam and a reference beam (usually a plane

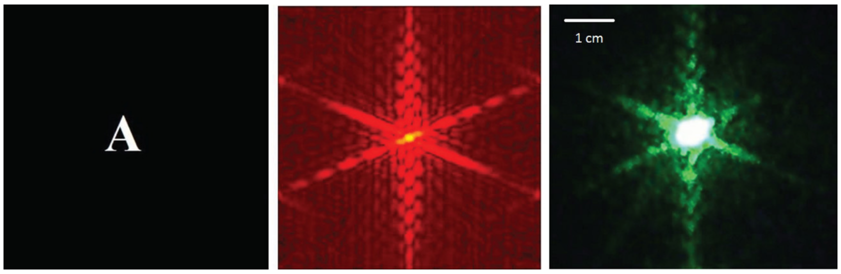

Fig. 5. Image of the letter A (left) and its simulated (center) and experimental (right) diffraction patterns. The image plane is approximately 2.2 m from the SLM.

wave). The object beam is then recreated by sending the reference beam through the hologram. In well-known examples of holography, the object beam is the light scattered from a common three-dimensional object. More generally the object beam can be any pattern of light, and this pattern will be recreated when the reference beam is diffracted by the hologram. Thus, a Fresnel zone plate, which focuses light through diffraction, can be thought of as a hologram created by interfering a focused beam (the object beam) with a plane wave (the reference beam). With a computer-addressed SLM, the zone plate can be tailored such that focussing is obtained for a desired wavelength of the incident light.

Mode conversion is another application of CGHs. With the appropriate holographic masks, SLMs have been used to create Hermite–Gaussian (HG), Laguerre-Gaussian (LG), and Bessel modes.[11,12] Here, we demonstrate the creation of the LG mode, also known as an optical vortex mode due to the twisted nature of its phase profile. To create the LG mode, the holographic mask must imprint an azimuthal phase distribution on the reference laser beam of the form $e^{i\ell\theta}$. The field continuity at $\theta = 2\pi$ imposes a requirement that ℓ can only take integer values. Since ℓ determines the number of phase windings that occur around the center of the beam in one wavelength of light, ℓ is called the "topological charge" of the vortex.[6] Moreover, each photon in a vortex beam carries an orbital angular momentum $\ell\hbar$.

The mask required for generating an LG mode can be obtained by considering a hologram formed from the interference of an object wave $e^{i\ell\theta}$ and a tilted reference plane wave e^{ikx}. This interference can be represented by the function

$$G(x,y) = \left| e^{ikx} + e^{i\ell \tan^{-1}(y/x)} \right|^2, \tag{1}$$

where k is the x-component of the wave vector of the reference wave. The mask pattern can be generated directly either from this intensity function or from a binary version of this function (Fig. 7(a)). When the light beam representing the reference wave diffracts from this mask pattern, the phase is imprinted on the laser beam and the optical vortex appears in the diffraction pattern. The topological charge used to generate the mask will correspond to the vortex formed in the first order diffraction. Figure 7(b) shows that the diffraction pattern consists of a central mode of topical charge 0, which is not an optical vortex, surrounded by diffraction orders with topological charge $n\ell$, where n is the diffraction order and ℓ the topological charge of the mask. As can be seen in the figure, vortices with higher topological charge have a larger distance between the central dark spot and the bright ring.

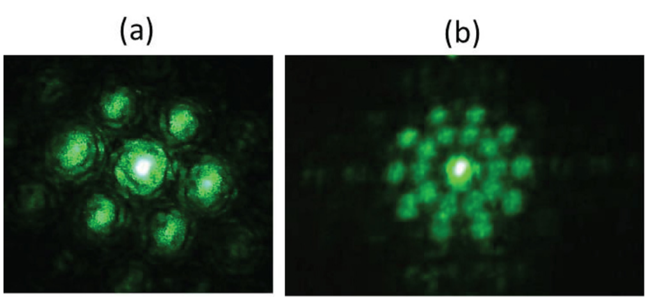

Fig. 6. (a) Diffraction pattern of a hexagonal honeycomb lattice. (b) Diffraction pattern corresponding to the crystalline structure of AlPdMn alloy, described in Ref. 9.

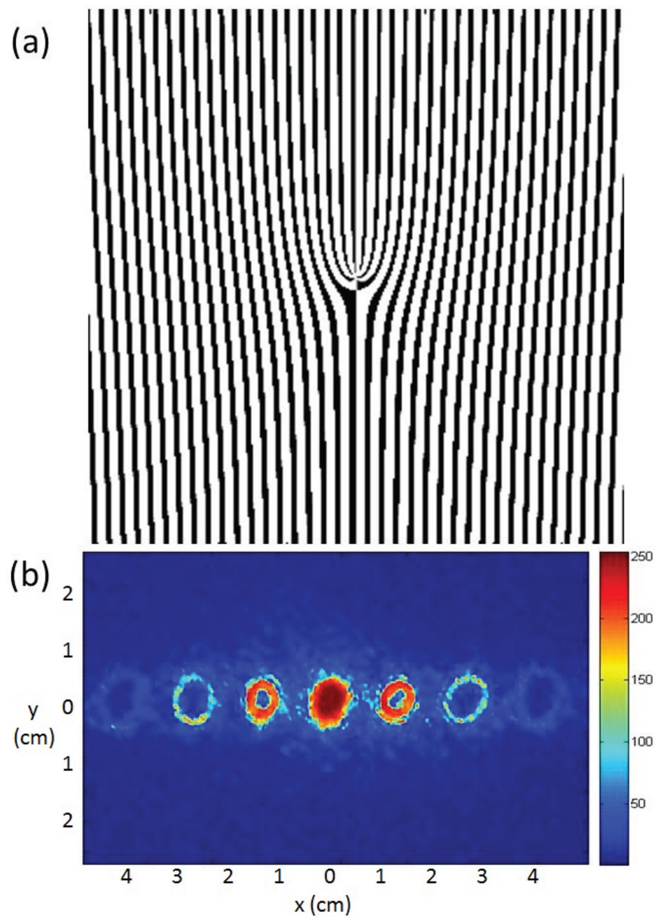

Fig. 7. (a) Holographic mask pattern produced using a contour plot of Eq. (1) with $\ell = 6$. (b) Optical vortices in the far-field resulting from the diffraction of the laser beam from this mask. The image to SLM distance is approximately 2 m. The scale represents light intensity in arbitrary units.

Table I. LCD specs for few economical used projectors.

Projector	Diag. Size (in.)	Resolution	Pitch (μm)
Infocus LP1000 (used here)	1.9	1024×768	36
Epson-EMP-73	0.7	1024×768	14
Mitsubishi-SA51U	0.9	800×600	23
EIKI-LC-X984	1.3	1024×768	26

Light vortices created in this manner can be used to implement novel experiments. It has been shown that by interfering the vortex beam and a reference beam having a spherical wavefront, one should observe an interference pattern of spiral arms extending from the center of the profile. Such an interference pattern suggests a twisted phase distribution of the light.[6] The orbital angular momentum of an optical vortex has been used to change the quantum state of Bose–Einstein condensates.[14] On the mesoscopic scale, an optical vortex can trap particles inside its dark spot due to the intensity gradient in the spatial profile. This property makes the optical vortex useful when incorporated into optical tweezers.[15,16]

The experiments we have conducted utilize the SLMs ability to modulate amplitude. It is also possible to modify the SLM to employ phase-only modulation.[8,16] Instead of using amplitude holograms, such as Fig. 7(a), a phase-only SLM can display phase holograms, which have greater diffraction efficiency. Such phase holograms have been used as kinoforms in optical signal-processing experiments to reconstruct images from diffraction patterns of arbitrary complexity.[8,17] Phase shaping has also been used to correct optical aberrations in a beam's wavefront,[18] and in femtosecond pulse shaping where phase compensation can lead to shorter pulse durations.[19]

To improve the SLM for experiments demanding better resolution, it may be desirable to obtain a more expensive projector with a higher pixel density LCD. An alternate approach is to expand the laser beam so that it encompasses a larger number of pixels. However, as we mentioned in Sec. II, it was not possible to expand the incident laser beam to the entire working area of the LCD because a beam diameter greater than 1 cm led to aberrations even in the zeroth order of the diffracted pattern. These aberrations are the result of the non-uniform thickness of the LCD module, which causes substantial spatial distortion of the wavefront of a large diameter beam. In contrast, a high pixel density LCD allows for more pixels to be enclosed in a smaller beam area, thus representing a better way to increase the effective resolution of the SLM. In Table I, we provide a comparison of the Infocus LP1000 LCD that we used here with a few other LCD elements typically found in other economical projectors.

Lastly, we note that it is possible to compensate for the poor optical quality of the glass substrate by bonding optical flats to the glass to improve the overall quality of the LCD.[20] Alternatively, submerging the LCD in a liquid gate filled with an index-matched material will also improve the quality.[21]

V. CONCLUSIONS

Modification of a used LCD projector is a very cost-effective way to obtain an SLM for undergraduate optics laboratories. We have described the procedure used to modify one particular model, but other projector models can be converted using the same basic process. Such an SLM setup enables hands-on experimentation with complicated diffraction masks and vividly demonstrates the Fourier transform concept in Fraunhofer diffraction. The SLM can also be employed for graduate-level research projects in phase shaping, holography, and optical control. We have also demonstrated the SLMs ability to generate optical vortices, which have many useful research applications.

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[a]Electronic mail: sandhu@physics.arizona.edu

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