Programmable Liquid Crystal Apertures and Filters for Photographic Lenses

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Abstract

LCDs (Liquid Crystal Displays) have become the ubiquitous low-cost display technology, with full color displays offering good resolution costing less than $10. Although LCD modules generally include either a backlight or a reflective backing, the LC panel itself merely modulates light by altering polarization. Thus, it is possible to use a transmissive LC panel as a programmable optical filter, or LCLV (Liquid Crystal Light Valve). This paper explores a variety of potential uses of commodity LC panels, including color panels, to implement programmable apertures and filters for camera lenses.

Introduction

This paper presents a highly experimental evaluation of the potential uses of LCDs (Liquid Crystal Displays) and LCLVs (Liquid Crystal Light Valves) as programmable filters, apertures, and shutters for photographic use. However, it is useful to first review some of the basic properties of liquid crystals to identify the expected issues in such applications.

Some crystalline solid materials have two melting points, and between them the material can flow like a liquid, but still has some attributes of a solid crystal at the molecular level. In this liquid crystal state, optical properties and thermal and electrical conductivity can be directional, or anisotropic. The optical result is light scattering and birefringence – separation of light into oppositely-polarized rays that propagate at different velocities. Although there are many types of both naturally occurring and man-made liquid crystals, the key attribute that enables LCDs and LCLVs is that applying a voltage can change the orientation of the molecules in an orderly way.

Figure 1 shows the basic construction of an LCD or LCLV. The "twisted" LC material is sandwiched between two transparent electrodes such that applying a voltage can proportionately "untwist" the LC molecules, thus rotating the polarization of light passing through the material. By further sandwiching that construction between two sheet polarizers typically oriented 90° rotated from each other, the changes in LC polarization angle can be made to continuously vary the angular alignment with the second polarizer. This allows control of the amount of light transmitted through the stack. By patterning one of the electrodes, the voltage can be applied selectively to specific areas of the LC material, thus allowing a wide variety of different shapes. Patterns include 7-segment digits, custom segment patterns for kitchen appliances and automotive instrument panels, and pixel matrix.

Although there are many different types of LC panels, one key distinction is between those that are actively refreshed vs. passively held. The LC material draws very little current, so the two spaced electrodes function somewhat like a capacitor, and applying a voltage and then disconnecting it will result in the LC polarization slowly reverting to its default twist. However, it is also possible to continuously drive the LC segment with the desired voltage, and that can be expected to produce more consistent polarization and thus better contrast. For example, TFT (thin-film-transistor) panels place an active refresh circuit with each segment or pixel; PMVA (passive matrix vertical alignment) do not.

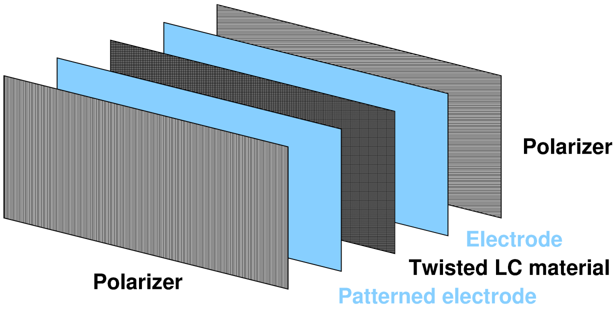

Figure 1. *Basic LC panel structure*

Figure 2. *LCLV set in 3D-printed 55mm filter, model and as built*

There is also the perhaps surprising fact that LC can wear out. If a DC (direct current) voltage is always applied to untwist the LC material, the molecular structure slowly loses its twist. The material can be expected to maintain its properties better when driven with an AC (alternating current) voltage that untwists in alternating directions. Often a controller bonded to the panel will implement this. Alternatively, because most microcontrollers are not directly capable of generating an AC signal on a pin, each electrode can be driven by a separate pin so that the relative voltage difference between them produces the desired AC signal.

Liquid Crystal Light Valves (LCLVs)

LCLVs are transmissive, usually transitioning between a naturally "clear" state and "black" with voltage applied. Very little power is drawn by these passive devices in operation and the most recent charge state slowly fades over periods of seconds or longer

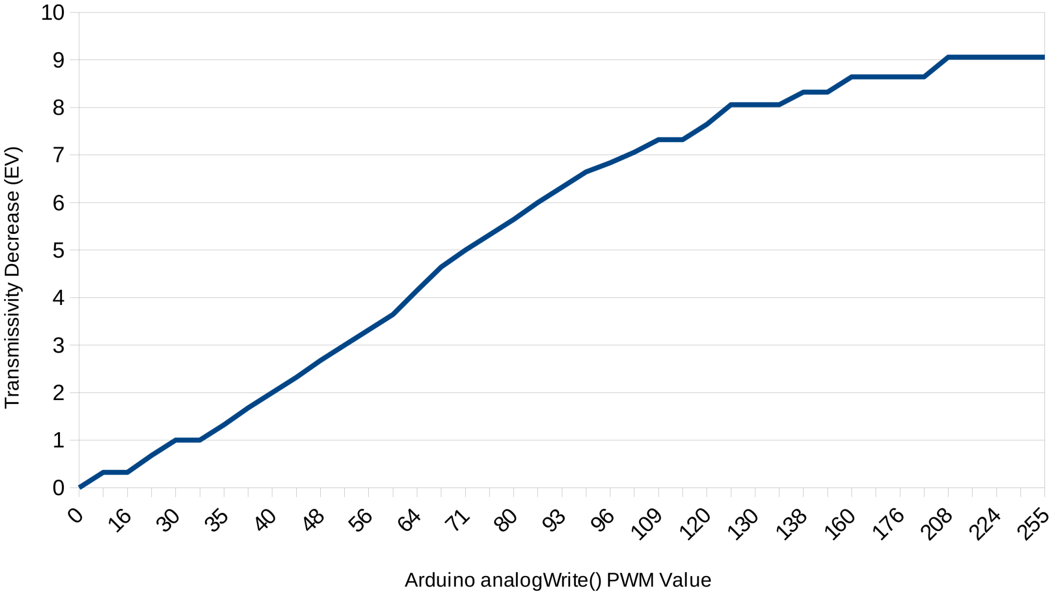

Figure 3. *LCLV filter*

after power has been disconnected. Most LCLVs have no patterning on their electrodes, hence they act as a single element with two leads. They are available at modest cost in a variety of sizes; very large panels are available.

Adafruit sells two LCLV panels, both TN (twisted nematic). The TN structure is one of the oldest and cheapest; it tends to have relatively fast response times and minimal smearing, but supports only relatively limited viewing angles. The Adafruit panels are:

- Part #3627, a 31x33x2mm panel costing $2.95
- Part #3330, a 96.5x38x2mm panel costing $7.50

Properties of both appear to be highly similar, rated to go from maximum transmissivity at 0V to minimum around 4-5V. The tests reported here were conducted on the smaller panels[1] because they have a shape and size more convenient for mounting as a standard threaded front-of-lens filter. An OpenSCAD program was created to design 3D-printable screw-in filter mounts for this in any of the standard thread sizes, although 55mm is the smallest standard size that allows the LCLV to be set entirely within the lens thread. The LCLV simply pushes into place with the two leads routed through the rectangular cut left for them, and a piece of black tape is used to prevent light passing through that area. The 55mm thread filter is shown in Figure 2.

The transmissivity of the LCLV filter is already significantly lower than clear optical glass due to the losses from the polarizers and the transparent electrodes. Light loss was measured as approximately 2EV (i.e., 2 stops) driving the LCLV to 0V. However, at 5V transmissivity dropped an additional 9EV.

Most microcontrollers, including the Arduino Pro Micro[2] used for testing, allow analog voltage output via PWM (pulse width modulation). It was not clear if the PWM output would allow good control of intermediate values, so a program was written to create an AC analog signal using two PWM analog output pins. The key is to keep flipping which pin is high, which can be done by repeated execution of code like:

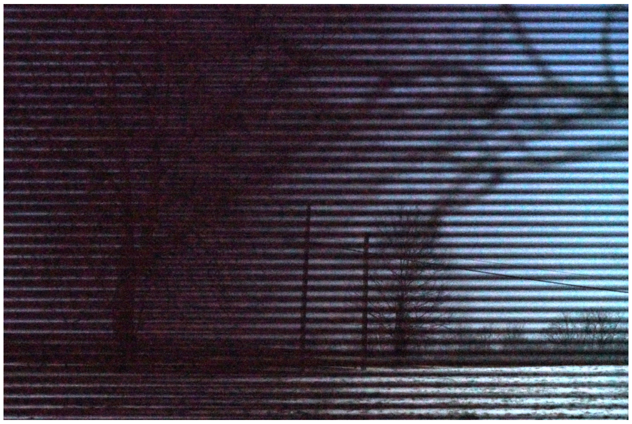

Figure 4. *Rolling shutter capture of repeated 1/2000s LCLV events*

```
a=pwm>>1; b=pwm-a; a=127-a; b=127+b;
swap=!swap;
analogWrite(shuta, (swap ? b : a));
analogWrite(shuta, (swap ? a : b));
```

in which `pwm` is the desired PWM difference value ranging from 0 to 255. As shown in Figure 3, the resulting transmissivity reductions in EV are surprisingly close to linearly related to PWM values for the lower half of the value range, but the curve flattens as the 9EV maximum is approached.

Going from 255 to 0 and then back to 255 was also found to produce a viable approximation to global shuttering, although time to darken is somewhat longer than time to clear. The crispness of the shuttering was tested using a Sony A7RII set to 1/8000s electronic shutter, thereby being able to use the rolling shutter speed to profile the rise and fall of the LCLV transmissivity. Figure 4 shows that LCLV implementation of a global shutter speed of approximately 1/2000s is viable.

Figure 5. *A sample scene captured directly, through the LCLV drive to 0V, and through the LCLV driven to 5V*

There are several other potential image quality issues that may be imposed by an LCLV filter, all of which can be judged from the test images in Figure 5. The first possible defect would be a color cast; however, colors in the leftmost and center images match well despite being shot without any filter vs. through the LCLV driven to 0V. It is worth noting that NIR (near infrared) transmissivity is very poor even when driven to 0V. LC materials are also known to impose some scattering (diffusion), which might also be imposed by the transparent electrodes; the same two images do evidence a slight drop in contrast when shooting through the LCLV, but the diffusion has very little effect on resolution and the lost contrast could easily be recovered by post-processing. The third defect is more literally a design parameter: LCLV panels commonly have their full polarization effect for only about +/-30° viewpoints from a reference viewing bias angle. The bias angle is a design parameter, often approximately 25° rather than 0° for viewing perpendicular to the plane of the panel. Close examination of the rightmost image, shot through the LCLV with the exposure calculated at 0V, but exposed at 5V, reveals that the filter is slightly less effective off center and particularly towards the bottom. Thus, the LCLV will be most effective if positioned to minimize the viewing angle variance from the manufactured bias angle.

A final concern involves the fact that light which has passed through an LCLV is linearly polarized, which may interfere with the operation of beamsplitters used in some cameras to divert light to separate phase detection autofocus (PDAF) or light metering sensors. This is known to be a problem in many film single-lens reflex (SLR) cameras, and continues to be an issue for digital SLRs. However, no significant problems were found in using the LCLV with mirrorless cameras. The standard solution for SLR polarizers is to convert the linear to circular polarization; this can be done by adding a quarter waveplate at the back of the LCLV.

In summary, the LCLV material tested is practical as an electrically-variable neutral density filter or global shutter. With an appropriately-patterned electrode, a multi-segment LCLV could be effective as a programmable aperture for implementing coded apertures or to shape bokeh with programmable apodization. Unfortunately, custom patterned electrodes have development cost in the $K range and significant production lead time. It was thought that perhaps a laser could be used to impose simple patterns on a standard LCLV, but quick tests with a 1W laser cutter determined that while a visible pattern easily could be produced on the LCLV, the electrodes remained conductive across pattern edges – it is not practical to segment an LCLV in this way after manufacture.

A Color LCD Panel

Although LCLV panels are not difficult to source, LCD panels are inexpensive and ubiquitous, and the common combination of color and pixel-level programmability might support more varied applications. LCD panels are available with a wide range of characteristics:

- LCDs can be color, grayscale, or monochrome. The difference between grayscale and monochrome is in the controller; a monochrome panel only allows on/off control of each pixel rather than multiple intermediate shades.
- Various patterns are common; pixel matrix arrangements are most common, but a variety of segmented patterns (e.g., 7-segment numeric displays) also are commonly available.
- There are a wide variety of drive and bias angle choices; color panels tend to be TFT devices often with a controller bonded to the panel to handle signal multiplexing. The controller usually accepts display data via an LVDS, MIPI, SPI, or I2C protocol; SPI and I2C are convenient to use with low-end microcontrollers, while the other interfaces offer higher pixel write speeds.
- LCDs are commonly sold not as bare panels, but as display modules. Backlit transmissive displays are most common, but reflective displays can be more easily viewable in sunlight and draw less power because there is no backlight. Backlit transflective displays can be used either as a backlit display or as a reflective display with the backlight turned off. Many LCD modules integrate a touchscreen, which is especially common for LCD sizes that have been used as cell phone displays.

For the applications of interest here, a transmissive display without a backlight is needed, and preferably also without a touchscreen. Removing the backlight from an LCD module sounds simple, and is for some larger LCDs (e.g., used in monitors or TV sets), but proved impractical for the smaller displays we examined. Contacting many United States suppliers of LCD panels in search of unbacked transmissive LCD panels revealed that these are not stock items; one supplier provided a link to a video showing how to remove the reflective backing from a reflective panel, but the backing is glued, and the panel is fragile enough that the panel always ends up with diffracting surface defects.

Bare unbacked panels are available from suppliers in China, however, cost and shipping delays were significant. The obvious alternative was to purchase a cheap LCD projector and extract the bare transmissive panel from that. The panel used for the experiments reported here was extracted from a WiMiUS S2 Mini

Figure 6. *Inside the WiMiUS S2 mini projector, the extracted transmissive color LCD panel, and magnified backlit view of the LCD matrix*

Projector, which cost just $55 new with two-day shipping and a free screen. As shown in Figure 6, relatively simple disassembly of this projector not only can provide a 100mm wide native 720P color LCD claiming a 5000:1 contrast ratio, but also a usable power supply and controller board accepting HDMI and other inputs. Although there are various differences, at least two other projectors from different manufacturers can provide functionally similar components; it is likely that most mini LCD projectors with native 640x480, 720P (often really 1280x800), or 1080P displays would be viable sources for parts.

The rightmost photo in Figure 6 shows a magnified backlit view of the LCD matrix with all pixels set to display white. As is typical of color LCD panels, each pixel is actually comprised of three separate sub-pixels filtered red, green, and blue. Thus, the 1280 horizontal pixels quoted are more precisely 3840 single-color-constrained pixels. Each pixel's subpixels form a square approximately 68.7 microns on a side, with opaque borders between subpixels.

Not surprisingly, there is a far greater light loss here than was experienced with the LCLV: approximately $4\frac{2}{3}$EV reduction in transmissivity. However, switching all pixels from white to black brings an additional reduction in transmissivity of approximately $9\frac{1}{3}$EV. That is slightly better than the LCLV delivered, but around 645:1 rather than the 5000:1 contrast ratio quoted for the panel. That said, a significant fraction of the panel is always opaque, so the 645:1 ratio is understating the contrast obtained in the active area of each pixel.

Most high-resolution color LCDs use a MIPI interface, which limits the speed with which pixel values can be changed – as does the HDMI interface on typical controller boards. Update rates faster than about 60 frames per second are unlikely, so this type of LCD is not usable as a high-speed global shutter.

To judge other image quality aspects, consider the scene image in Figure 7. Put bluntly, this image is unusably poor – but why? In close examination, it becomes clear that diffusion, while present to a modest degree, is not the main problem. The key defect is diffractive repetition of scene features.

From the rightmost photo in Figure 6 it can be seen that the fill factor for pixels is about 85%. Pixel rows are separated by thick mullions spaced approximately 68.7 microns on center. Columns have much thinner mullions, only about 22.9 microns on center due to the subpixel structure. Ignoring the color filters, the LCD panel essentially forms a diffraction grating with different horizontal and vertical spacings. The diffraction angle θ imposed by a grating is a function of the light wavelength λ, line spacing d, and order number m: $\theta = sin^{-1}((m \times \lambda)/d)$.

Figure 7. *Sample scene captured through front-mounted color LCD*

Plugging in λ values of 450nm for blue, 530nm for green, and 600nm for red yields $m = 1$ angular displacements of over 1° in the horizontal and about $1/3$ as much in the vertical. If the LCD is being imposed in a position within the optical path where such angular deflections of light are not important, such as very near the plane of focus, the corruption of the image would be minimal. However, Figure 7 was shot using a 3D-printed front-mounted screw-in filter adapter. The result is that the image suffers some vertical smearing, but image content is strongly echoed approximately shifted horizontally by 60-90 pixels (using a normal lens on the 42MP Sony A7RII). The $m = 2$ horizontal shifts also are visible, but dramatically less intense. The horizontal artifacts are probably also amplified by the red, green, blue subpixel filtering; although we did not model this effect, there is a color bias in the shifted images.

There are several ways in which this diffraction grating problem could be significantly reduced:

- Perhaps the most obvious attack is simply to change the grating. Using a coarser grating – a lower resolution display with correspondingly larger pixels – could dramatically reduce the artifacting. Even at the same pixel size, grayscale LCDs do not have the subpixel structure that amplified the horizontal angular shifts using this color panel. It also would be possible to use custom segment (pixel) layouts that are sized and/or shaped to minimize grating effects. Finally, at the cost of a significant reduction in contrast, the mullions between pixels in a custom panel could be made at least partially translucent.

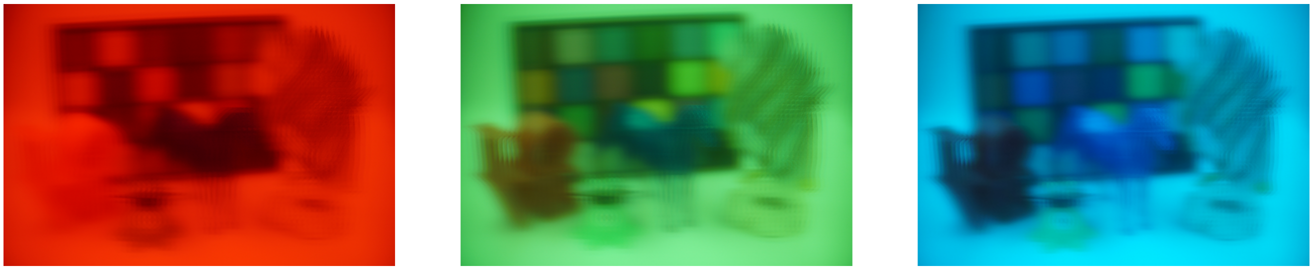

Figure 8. *Sample scene captured through front-mounted color LCD with pixels set red, green, and blue*

- High-quality computational repair in postprocessing seems unlikely, but placing the front camera of a cell phone behind the display (as opposed to within a notch) causes closely related problems that are the subject of many recent research papers. In fact, the two papers presented before this one at the Electronic Imaging 2021 conference are both about use of machine learning to implement computational repairs for under-display cameras. It is important to note that displays cell phone cameras are under are designed to have sparser pixels in a transparent field for the display area in front of the camera, and even more significantly the displays use OLED technology, not LCD.
- It is conceptually possible to directly treat an LCD grating as part of the optical design of a lens, building-in appropriate correction. However, this seems particularly difficult and likely to be prohibitively expensive.

Despite the diffraction issues, the color performance of the LCD panel is actually quite good. Overall color shift in the all-pixels-white image was less than 1%. Figure 8 allows more precise evaluation of the individual color filters. All three are good, however red is purer than blue, which is in turn purer than green. Mixing colors works as expected, with good control. Certainly, this type of panel could be very effectively used to spatio-temporally control color of a light source – then again, that's exactly what it was doing in the projector it was extracted from.

Compared to the LCLV, the polarization effects in this LCD are significantly stronger, which is to be expected from an actively-refreshed TFT panel. The bias angle seems to be approximately 0°, which is fitting for application in a projector, and the polarization seems to hold up better at various viewing angles than was seen with the LCLV panel. As for LCLV, addition of a quarter waveplate would probably still be necessary for use with cameras containing beamsplitters.

In summary, the high-resolution pixel matrix transmissive color LCD panels are not useful as high-speed global shutters because the controller logic limits pixel change rate. There also are very serious problems linked to behaving as a diffraction grating; these diffraction effects would impede most uses as programmable filters or apertures. However, all other properties are actually better than one might expect.

Existing applications

There are surprisingly few published works involving programmable filters and apertures. However, there are several types of applications for which the LC panels evaluated here may be appropriate.

Use of an LC array to sequence coded aperture patterns that allow direct capture of a lightfield was explored by Liang et al[3]. Their work was done using an LCLV patterned with 5x5 pixels, each approximately 6x6mm. The pattern had clear gaps between pixels, and they did not quote an EV drop for dark pixels, but noted that the pixels could not be completely turned off; they dealt with both issues by subtracting a "dark frame." Their approach is essentially a way to make a plenoptic camera without trading image pixel count for number of ray angles distinguished. From the measurements made in the current work, it is obvious that the large size of their pixels made diffraction a non-issue, but significantly higher numbers of ray angles could be distinguished before diffraction would be problematic. The 9EV reduction in light passed by a dark LC element would impose a second limit involving dynamic range; assuming dark gaps between pixels, an evenly-lit scene captured through an LC pattern with about 512 elements would be leaking as much light as a single clear element would pass.

Nagahara et al. used a reflective LCoS (Liquid Crystal on Silicon) device to implement a general-purpose programmable aperture[4]. The reflective nature of LCoS resulted in a complex construction for their camera involving relay lenses to create a patterned virtual image plane that could be photographed using the primary lens. Their 1280x1024 pixel aperture patterns do not appear to have the same diffraction effects observed using the color LCD panel in this paper, and their controller allows a much higher framerate for changing the pattern than the LCD used here supports. However, the actual contrast they measured was 221:1, which is significantly lower than was measured from the LCLV and LCD panels here. In summary, the primary limit on LC panel use again seems to be diffraction for higher pixel count LCDs.

The same LCD pixel-size that causes diffraction problems also can be treated as a programmable array of pinholes, as was done in the lensless imaging work of Zomet and Nayar[5]. The contrast ratios they measured were 14:1 or less, which required work-arounds that the current work suggests should not be needed with modern LCDs.

Although not directly referring to a programmable aperture, single pixel imaging[6] is another existing application domain that could leverage the LCD panels evaluated here. The transmissive SLMs (Spatial Light Modulators) used in a variety of systems are essentially grayscale TN LCDs sold without the outer polarizers. It would also be possible to use a color LCD in a way resembling how DMD (Digital Micromirror Devices) are used for single-pixel imaging. In such an application, the LCD panel would be placed in the focus plane with a large or diffused single-pixel sensor behind it so that the sensor integrates the light from all clear pixels. This approach offers a number of potential advantages. For example, it might be possible to implement a large-format color camera in which a cheap color LCD and a single light sensor could potentially replace what would be a very expensive large-format sensor, although the LCD framerate and 9EV contrast would limit performance.

Conclusion

The empirical evaluation of LCLV and color LCD panels presented here suggests that there are photographic applications for which these devices are highly suitable. Simple LCLV panels work very well as controllable filters or global shutters, and with custom electrode patterning easily could serve as programmable apertures for implementing programmable apodization, bokeh shaping, and coded apertures to facilitate reconstruction of depth information. Transmissive color LCDs also had many favorable properties, but a high-resolution pixel matrix is a diffraction grating, so various work-arounds must be applied. The time taken by the controller interface to change all pixel values in the matrix also limits performance on these LCDs as a shuttering mechanism.

Two areas for future research were revealed in this study. Custom segment patterns for LCLV apertures seem particularly promising. In addition, the diffraction caused by a color LCD panel is not problematic when positioned close to the image plane. Thus, there is good potential to use a color LCD as a large-format light modulator for single-pixel imaging.

Additional materials, such as the 3D-printable filter holder designs, will be available at:

`http://aggregate.org/DIT/LC`

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