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Synthesis of a color image display using birefringent filters

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Abstract. A new method of generating color in liquid crystal displays using birefringent filters is shown. This method has the benefit of high light transmission and color saturation compared to traditional spatial or temporal multiplexing methods, which include highly absorptive color filters. We discuss the design and optimization of a double-layer super-twisted nematic color display based on polarization interference filters. The viewing angle of such a device is also modeled and improvements are shown. The device is capable of high light transmission (90% that of parallel polarizers) while retaining color saturation.

Subject terms: liquid crystal; display; liquid crystal modeling; Solc; Solc filter; polarization interference filter; stacked; stacked display.

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1 Introduction

Traditionally color generation in liquid crystal displays (LCDs) is accomplished by the patterning of color filters onto individual pixels, resulting in a loss of resolution due to subpixeling as well as lowered light transmission due to the absorptive nature of the filters. Other methods of generating color include field sequential color in which the actual color is generated by RGB light emitting diodes (LEDs) and the LC pixel is driven so as to either block or transmit the colored light. This typically requires the LC to be driven at a very high frame rate, which in turn calls for a very fast switching LC material and mode; and such materials and modes are difficult to find. Another method of color generation is by the use of polarization interference filters (PIFs). Such a filter works by introducing a phase shift between two orthogonally polarized field components by either a static or dynamic optical element such as a uniaxial retarder or electrically driven LC cell. Color is generated by the interference of these two components with an analyzer, color switching is accomplished by changing the phase shift between the two components by using dynamic optical elements. Since there are no more losses other than the ones associated with polarizer absorption, the PIF can generate color with a higher luminance than absorptive color filters.

The use of retarders between polarizers to function as filters has been studied for several years, starting with the original design by French astronomer Lyot\textsuperscript{1} for monochromatic imaging. The Lyot filter design was improved on by the Solc\textsuperscript{2} design, which offered similar filtering characteristics but higher overall transmission. The Solc design was then generalized by Harris et al.\textsuperscript{3} in a paper that described a synthesis procedure for obtaining various filter designs. The two original Solc designs are the “fan” and “folded” type.

In the fan design, the wavelengths at which the elements have an even number of half waves of retardation pass through an output polarizer oriented parallel to the input polarizer. In the folded design, the wavelengths at which the elements have an odd number of half waves of retardation pass through the output polarizer, which is crossed with respect to the input polarizer. The passband characteristics of the Solc filters are directly related to the number of elements used to create the filter, i.e., the larger the number of elements the sharper is the passband. Another crucial element in the transmission function is the size and frequency of the sidelobes. As it turns out the Solc filters are not optimal in design and give passband sidelobes that can be avoided using various synthesis techniques.\textsuperscript{3}

2 Polarization Interference Filter Design

The use of PIFs for the generation of color in a display device was shown by Sharp and Johnson.\textsuperscript{5} Starting from a Solc filter design, the design of a device capable of switching between a single color and black or white, depending on the polarizer orientations, was shown. The operation of this design is fairly simple. Given that a folded Solc filter will filter the design wavelengths by rotating them by $\pi/2$, then to be able to switch between a filtering and nonfiltering action, a second active optical element must be added to the filter. The addition of a single switchable half-wave plate placed between the filter along with a repositioning of the second half of the filter is all that is required. The repositioning required is simply inverting the order of the second half of the filter and rotating it by $\pi/2$, as shown in Fig. 1.

The switchable half-wave plate can be an LC cell or any other switchable electro-optic element. If the LC cell is switched so that its net retardation is zero, then the first part of the filter is crossed with respect to the second part of the filter, as shown in Fig. 1. In this case, the net retardation between the two polarizers is zero and so the display appears black for crossed, and white for parallel polarizers. If the LC cell is now switched so that it is a half-wave plate, then its effect on the filter depends on its orientation in the
As shown in Fig. 1, light entering the filter from the left will have the desired wavelength rotated by $\pi/2$, while light entering from the right will be rotated by $-\pi/4$ to $3\pi/4$. Therefore, for light to pass through the complete filter, the LC cell must take light polarized at $\pi/4$ and rotate it to $3\pi/4$ deg, a $\pi/2$ rotation easily accomplished by placing the LC cell at $\pi/4$ to the incoming polarization. In this position, the LC cell enables the filter to be switched on or off, depending on its own state. For intermediate voltages, the LC cell acts as a retarder between 0 and $\lambda/2$ and so rotates the incoming linearly polarized light to some elliptical state. As a result, the desired wavelength is not completely rotated by the second half of the filter and so suffers absorptive losses at the analyzer. In this manner, intermediate gray-scale colors can be created.

The effect of the filter on the rest of the spectra is as follows. In the case of a pure folded Solc filter, the undesired wavelengths entering the filter linearly polarized at 0 deg are all left unrotated (more so for a multiple plate retarder than a two plate) and are absorbed at the analyzer, which is crossed with respect to the polarizer. For the preceding design, the placement of the LC cell ensures that the polarization state of the unwanted spectra remains untouched. While the desired wavelength is rotated to $\pi/4$ by the first part of the filter, the rest of the spectra remains at 0 deg. In doing so, these wavelengths are at $\pi/2$ to the LC cell optics axes and so the LC cell has no effect on them. Passing through the second half of the filter, they remain linearly polarized at 0 deg and are absorbed by the analyzer.

Therefore, in summary, the design requires the following:

1. A polarizer provides linearly polarized white light at a known orientation.
2. A prefilter rotates the linear polarization of the desired spectra to an angle of $\pi/4$ with respect to the optic axes of the LC cell while leaving the polarization state of the rest of the spectra untouched.
3. An active optical element such as an LC cell rotates linearly polarized light by $\pi/2$, i.e., a half-wave plate, and has no effect on light polarized along or orthogonal to its optic axes.
4. The postfilter is a copy of the prefilter, except it is inverted and rotated by $\pi/2$.

This filter design is capable of producing a relatively narrow passband transmission function (depending on the number of retarders making up the prefilter and postfilter) and so can produce a single color or its gray shades from input white light. Such a filter was discussed in detail in previous work. To produce more than one color, i.e., red, green, and blue, a stacked approach must be taken. In the stacked approach, the preceding filter design is tuned for each of the three primary colors and then stacked one on top of the other. Only one polarizer and analyzer are used at the two ends. The stacked design works since each stack rotates only the wavelengths associated with its color, i.e., the blue stack is designed to rotate wavelengths 430 to 490 nm, while the rest of the spectra is left linearly polarized at 0 deg. As the analyzer has now been moved out to the end of the stack, this part of the spectra is able to move through the other two stacks, as shown in Fig. 2.

Since the entire white light spectra is able to move through the three-layer stack with each layer affecting only its designed wavelengths, the stack can produce red, green, blue, and white light or any combination. This, however, will be true only if the RGB spectra do not overlap. As mentioned before, the bandwidth of each filter depends on the number of elements making up the filter. If only four retarders are used, then the filter bandwidth would be quite broad. If this filter was to be placed in the stacked design, it would rotate parts of the undesired spectra along with the desired spectra. For example, if the red filter is broadband, then it will rotate parts of the green spectra also. As a result, if the stack is set up to be in the white state, i.e., all three layers are rotating their design wavelengths, then the green would be overrotated, and the resulting white output would lack some green. Therefore, in a stack design it is important to have each filter bandpass be as narrow as possible so as to prevent overlap, which would reduce efficiency.

2.1 Synthesis of Stack

There are a number of orientations that the retarders making up the filter can have and still provide similar if not identical transfer functions. Synthesis techniques described by Harris et al. and Buhrer are useful to obtain the best orientations of the filter elements for a required transfer function. Synthesis techniques rely on the fact that each element in the filter provides one cosine Fourier component of the desired transmission function. Such synthesis techniques are useful in situations where the active element in the filter operates in the 0 to $\lambda/2$ regime. In the case of more optically complex active elements, such as supertwisted nematic (STN) cells, it is easier to use computer modeling to obtain the required orientation and retardation values.

In a previous paper, we discussed the design of a birefringent filter based LCD employing electrically controlled birefringence (ECB) type cells, which fall into the cat-
category of optically simple active elements. The ECB type cells, however, require a rather expensive drive method called active matrix addressing, which involves the use of a transistor at each pixel edge to provide switching operation. On the other hand, the passive matrix method makes use of the sharp electro-optical characteristics of the LC mode and can drive decent sized displays without the use of transistors, and as a result is cheaper and easier to manufacture. However, the requirement of a sharp electro-optical curve means that LC modes such as the ECB cannot be used, and so an STN mode must be used instead. The STN cell, however, has a relatively complex optical characteristic due to its highly twisted structure. It no longer acts as a waveguide, and so output polarization states are generally never linear in nature. As a result of this, the STN cannot be substituted for an ECB cell in a working filter design. Also, the fact that the STN must be driven at two voltages, neither of which has an isotropic output, means that it cannot be used in the filter designed for an ECB. By having no isotropic output it is understood that no matter what orientation linearly input light has with the STN’s optic axis, the STN will always change its state. This is unlike the ECB cell case where light linearly polarized at 0 deg or π/2 with respect to the optic axes passes through unchanged, and is a fundamental requirement for the filter design.

To satisfy the requirement that in one state the active element has a net zero retardation, the use of a double-layer STN (DSTN) was employed. The DSTN cell uses two STN cells made of the same LC material. One cell can be driven and has either a left- or right-handed twist, while the other cell is placed orthogonally with respect to the first, and has the opposite twist. As a result, when the first cell is in the nonselect state similar to the second, the two cancel each other out and appear optically isotropic, thereby satisfying one of our requirements. In the select state, the first cell is driven while the second is left as is and so the DSTN appears optically active.

The second requirement of having an orientation at which light input linearly polarized passes through untouched is a lot harder to satisfy by just looking at the DSTN, and the complex optics of its cells’ driven and undriven state. This requirement must be satisfied since only the desired wavelength should be rotated, leaving the rest of the spectra untouched. If the DSTN was to rotate any other part of the spectra, then in a stacked design the successive filters would not have 100% of the spectra to work with, and so colors would leak and efficiency would be considerably lower.

To obtain the best orientations and retarder values, computer modeling was employed to optimize the stack. A four-layer stack was designed and computer simulated to obtain the best orientation and retarder values. The four-layer stack is shown in Fig. 2.
uniaxial retarder (two prefilters and two postfilters) and one active element (DSTN) filter was chosen, as shown in Fig. 1. The number used here was for the sake of example. Any number of retarders could be used since the more retarders are used the better is the filter performance. The STN mode was chosen to be a 180-deg twist with parameters and director profiles at select and nonselect voltages, as shown in Fig. 3.

The extended Jones matrix method\(^9\) was used to obtain the spectral output of the stack. Even though obtaining the spectral response of a single configuration of the complete stack is a relatively fast operation on a desktop computer, the sheer number of possible orientations of all the elements in the stack makes it impossible to model the entire R, G, and B filter stack put together. As a result, a single color stack was modeled between crossed polarizers. The retardations \(R_1, R_2\) and orientations \(\alpha_1, \alpha_2\) of the first two retarders (prefilter) in the stack were allowed to vary as well as the retardation of the LC \(R_3\) used in the DSTN and the DSTN’s orientation \(O_3\). The last two retarders in the stack used the same retardances as the first two, except inverted \((R_2, R_1)\) as well as orthogonal \((\alpha_2 \pm \Pi/2, \alpha_1 \pm \Pi/2)\) as required by the design. The orientation of the retarders was changed from \(-90\) to \(90\) deg in 15-deg steps and their retardation changed from \(200\) to \(1000\) \(\text{nm}\) in 20-nm steps. The DSTN angle was changed from \(-90\) to \(90\) deg in 15-deg steps also, and its retardation from \(500\) to \(1900\) \(\text{nm}\) in 20-nm steps. For each of these combinations, transmission values were calculated at three different wavelengths. For example, the blue stack light transmission was calculated at 430, 550, and 650 nm. Assuming a transmission function similar to the one shown in Fig. 4 for the blue filter to be optimal, the characteristics of the elements were written to file if the normalized transmission at 430 nm was greater than 0.5, for 550 nm less than 0.125, and less than 0.05 for 650 nm. Only three points are used for the calculation due to the time it takes for each calculation, and the number of different combinations. The same is done for the green and red filter cases with wavelength points and threshold values. If the transmission for each filter satisfied, the given thresholds the retarder and DSTN characteristics were written to file.

The outputs for the R, G, and B filters were then further refined. This was done by reading in the files obtained from the preceding step and aligning the retarder for example \(\pm 5\) deg around the given value. In this case, the DSTN retardation was varied \(\pm 10\) \(\text{nm}\) and its angle \(\pm 5\) deg around the given value. Only the angular value of the retarder was changed by the \(\pm 5\) deg. For each possible combination, the transmission at wavelengths similar to the preceding case were calculated and compared to the same threshold. If the new orientations satisfied the threshold they were written to the file. In this way a finer orientation can be obtained.

### Table

<table>
<thead>
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<th>Twist</th>
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<td>Thickness</td>
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<tr>
<td>Pretilt</td>
<td>5°</td>
</tr>
<tr>
<td>Elastic Constants</td>
<td>(K_{11}=10, K_{22}=7, K_{33}=18)</td>
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<tr>
<td>Dielectric Constants</td>
<td>(\varepsilon_{app}=15, \varepsilon_{epp}=10)</td>
</tr>
<tr>
<td>(V_s, V_{ns})</td>
<td>2.44, 2.10</td>
</tr>
<tr>
<td>(d/p)</td>
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</tbody>
</table>

**Fig. 3** Calculated director tilt and twist profiles at \(V_s\) and \(V_{ns}\) for the STN parameters used.

**Fig. 4** Plot of optimal blue filter performance. The transmission is normalized to peak transmission of parallel polarizers. The lower transmission is due to the low light throughput at these wavelengths by the polarizers modeled.
around values we know work. This significantly reduces the computation time compared to if the original search was done with a finer angular resolution. In the next step, each of the configurations from before were read from the file, and for each configuration, the transmissions at different wavelengths were calculated. In the case of the blue filter, for example, 550-, 600-, 650-, and 700-nm wavelength values were used. This was done to eliminate configurations that had significant leaks at those wavelengths, signifying that more than one maxima or a large sidelobe existed in the transmission function. This process eliminated a number of configurations that were dissimilar to the desired transmission function. The configurations that did satisfy the thresholds were written to the file for each filter.

Next, these configurations were read from the file and further refined. In this step, only the retarder angles were refined by allowing the angles to float $\pm 5$ deg from the ones read in from the file and varied in 0.25-deg steps. This was done to pull out possible Solc-defined angles for a filter using two retarders. The same threshold conditions as in the preceding step were applied and the configurations satisfying the threshold were written to the file.

To rank the configurations obtained for each filter, the Commission Internationale de l’Eclairage (CIE) 1931 color coordinate for each configuration in the file was calculated. For each coordinate, its position with respect to the NTSC color coordinates was calculated. The configurations were then ranked from closest to farthest from the NTSC color coordinate for each filter. However, the proximity to the CIE color coordinate alone does not signify that the configuration was the best, since its overall luminance can be low. As a result, the first 100 configurations were plotted and the one with the brightest output was chosen.

Using this method, the orientation and retardation of the elements making up the three different color filters were chosen. By ensuring high peak brightness at the desired wavelength along with sharp transition slopes and minimum overlap, it can be assumed that the filter is rotating the desired wavelength by $\pi/2$ and leaving the rest of the spectrum unchanged, thereby fulfilling condition 3 defined earlier. The spectral response of the three filters put together to form a complete stack is shown in Fig. 5(a) along with the CIE coordinates in Fig. 5(b). The lower transmission of the blue and green state is due to polarizer characteristics at those wavelengths and not due to the filter design. The polarizer’s maximum transmission at those wavelengths is what the filter is transmitting. The stack details are shown in Table 1.

Since the optimization is done using single-color filters, and some colors such as green have a inherently wider passbands, the position of that filter in the overall stack has an effect on the white state. The white state is where all

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Table 1 DSTN and retarder orientation and angles for the three filters making up the stack.

<table>
<thead>
<tr>
<th></th>
<th>Green</th>
<th></th>
<th>Blue</th>
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<td></td>
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<td>Retardation (nm)</td>
<td>Angle (deg)</td>
<td>Retardation (nm)</td>
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<td>750</td>
<td>$-40$</td>
<td>1150</td>
</tr>
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<td>$-40$</td>
<td>600</td>
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<td>500</td>
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<td>$-70$</td>
<td>800</td>
<td>$-14$</td>
<td>800</td>
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<td>500</td>
<td>20</td>
<td>800</td>
<td>76</td>
<td>800</td>
</tr>
<tr>
<td>$R_4$</td>
<td>700</td>
<td>50</td>
<td>600</td>
<td>$-75.5$</td>
<td>500</td>
</tr>
</tbody>
</table>
three filters rotate their design wavelengths. The stack was modeled by placing the optimized filters in various positions in the stack, i.e., BGR, GBR, GRB, RBG, etc. From this, it was ascertained that the GBR position was the best. In all the different positions, the spectral response of the single-color state was similar as well as the black state. The white state was the only one that changed due to the green cells’ relatively broader passbands rotating certain parts of the blue and red spectra. The spectral response of the white state is shown only for the BGR and GBR states in Fig. 6. The GBR state was chosen as it has a dip in the blue part of the spectrum as compared to the BGR orientation, which has a dip in the red. Since most backlights are red lacking, it was decided to use the GBR orientation so as to maximize red throughput in the white state. The BGR and GBR white points are shown in CIE diagram Fig. 5b and the lowered red transmission of the BGR configuration is visible in terms of a shift in the white point to the left. The GBR white point is more centered.

### 3 Viewing Angle

The viewing angle (VA) of the complete device was also calculated and is shown below for several off-axis angles. As can be expected and as observed, the VA of the device deteriorates rapidly due to the three STN cells.

The black state light leakage of the device is shown in Fig. 7(a) for the optimized stack and two other configurations for viewing angle cones of 10, 20, and 30 deg. The optimized stack has three STN cells at 5, −40, and 40 deg with respect to the polarizer. Figures 7(b) and 7(c) show configurations that have all the STN cells at −50 deg, and at −40, 50, and 50 deg, respectively.

The light leakage for the optimized configuration deteriorates rapidly and at 30 deg off axis is no longer black. To understand and reduce this leakage another configuration in which all the STN cells were at 50 deg was modeled. The thought behind this was to try and see if the viewing characteristics would be more uniform since all the cells were at the same angle and perhaps better results could be obtained in at least one hemisphere. Figure 7(b) shows the results for this configuration, which indicate only a slight improvement in the second and third quadrants and worse in the first and fourth. The next configuration tested was one in which the cells were crossed with respect to each other to try and cross out some light leakage. The configuration used was one in which the first cell was at −40 deg and the second and third were at 50 deg. This configuration shows a significant improvement over the first two. The white state and single-color state VAs are also shown for the optimized and −40/50 deg configuration in Figs. 8(a) through 8(d).

In the white state, the two configurations are about equal with the −40/50 deg configuration, offering slightly better results for larger cone angles. In the single-color on state, the −40/50 deg configuration is once again better than the optimized configuration, showing a better response for the 30-deg viewing cone. The −40/50 deg configuration...
showed a similar spectral response as the optimized configuration, however, with a lower overall red transmission, as shown in Fig. 9(a). The CIE coordinates are shown in Fig. 9(b), and Table 2 shows the stack details.

Another method of obtaining a better viewing response from a STN cell was described by Hoke et al. The method involves using negative birefringent material for the compensator part of the DSTN. The compensator is then placed...
so that each layer of the compensation cell is a mirror image of the active STN cell in the nonselect state. The application of such a film onto the active cell is expected to enhance the overall viewing angle of the device, much more than the compensation cell used in the DSTN design. The performance of the display with such a film is being investigated and will be reported later.

4 Conclusion

The design of a polarization interference-filter-based design was shown using DSTN cells as the active switching elements capable of being driven using a passive matrix method. The device design and optimization was shown as well as the viewing angle characteristics. The device also provides an excellent color gamut with saturated colors. The V\(_A\) of the device was limited due to the use of STN cells, but was shown to be improved using alternative orientations. The viewing angle could also be improved by using negative birefringence films in place of the compensator cell and its effects are currently being modeled.

Acknowledgments

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References

Salman Saeed received his BA degree from the College of Wooster, Ohio, 1996 and joined the Liquid Crystal Institute at Kent State University, where he is currently a fifth-year doctoral student. He is working in the labs of Dr. Philip J. Bos on optical modeling of liquid crystal displays and other liquid crystal technologies.

Philip J. Bos received his PhD degree in physics from Kent State University in Ohio in 1978. After a year as a research fellow at the Liquid Crystal Institute at Kent State, he joined the Tektronix Laboratories in the Display Research Department. In 1994 he joined the Liquid Crystal Institute and became a professor of chemical physics. He currently has several projects in the area of applications of liquid crystals. He has over 80 publications and 20 patents.