1. Introduction

For near and front projectors as well as for near eye applications, time-sequential color switching is of increasing interest. It allows to successively process the image information for the three primary colors. This is a premise for all projector configurations which are based on a single imager. Time-sequential addressing reduces complexity, cost and size of projectors compared with conventional triple beam configurations.

Prerequisites for realizing time-sequential addressing are fast responding color filters and imagers which are synchronized. Because of their microsecond response times at low driving voltages, ferroelectric liquid crystal cells and photo-aligned, non-absorbing liquid crystal polymer thin-films.

Abstract

We present a novel thin-film based electro-optical concept of a fast responding electronic color switch with optimal transmission and a color gamut meeting NTSC standard. The versatile and compact polarization color switch consists of ferroelectric liquid crystal cells and photo-aligned, non-absorbing liquid crystal polymer thin-films.

A complete color switch consists of three BMF modules, one for each primary color, placed in series. A full color electronic BMF switch permits to successively select the transmission of one primary color with time resolution below 100 μs at 15 V driving voltage, while simultaneously acting as a high quality, non-absorbing broadband polarizer [2-5]. Because electronic BMF color switches do not comprise any absorbing optical elements, almost ideal transmission and excellent light stability result.

Moreover, because the transmission characteristics of our BMFs can be adjusted, they exhibit a high degree of optical design flexibility regarding brightness and color purity. The inherently high brightness of BMFs can be further enhanced by additional polarization conversion in front of the color switch [6]. Stacking of crosslinkable chiral and non-chiral photo-aligned liquid crystal polymer thin-films developed in our laboratories [7] enables an integration of all BMF functional optical thin-films directly on the substrates of the FLC switches. This permits a very compact, stable and rugged electronic color switch design.

One drawback of our earlier BMF configuration, which is remedied in the new arrangement described below, is the sensitivity of its blocking state against variations of FLC retardation due to cell gap inhomogeneities. When the FLC switches did not meet tight optical tolerances, residual transmission and reduced color saturation resulted. Moreover, the former concept of three independent BMF modules, which are configured not to influence the light outside their wavelength bands, prevents a simultaneous optimization of both color purity and brightness. This is caused by the fact that an efficient splitting of white light into three saturated primary colors requires on the one hand band pass filters with a certain range of overlap between the blue and the green wavelength bands and on the other hand a gap between the green and red bands. A transmission gap can easily be realized by means of a cholesteric notch filter. Overlapping bands were, however, not realizable with our earlier BMF design. The reason for this is that applying independent BMFs with a blue-green overlap transmission in both the blue and the green frame times would inevitably lead to an undesired blue-green transmission also in the red frame time, which would degrade the color gamut of the BMF color switch. Our novel electronically switchable BMF color filter configuration remedies these earlier drawbacks.

2. The Electronic Band Modulation Filter

Figure 1 (a) depicts the BMF modules of which our electronic color switch is made up. Each of the three BMFs is designed to transmit or to block one of the primary colors depending on its switching state. The achromatic λ/4-plate at the output of the BMF color switch converts the circularly polarized light loss-free into linearly polarized light.
Each BMF consists of an FLC cell between two $\lambda/4$-plates and two cholesteric filters (figure 1 (b)). Contrary to our earlier design, both cholesteric filters now exhibit the same handedness. Within the selective wavelength band one of the two circular components of unpolarized input light exits the first cholesteric thin-film filter and is converted into linearly polarized light by the first $\lambda/4$-plate. The FLC cell acts as a $\lambda/2$-plate whose optical axis is electronically switchable by 45°. In the on-state of the FLC cell (upper part of figure 1 (b)) the field vector of the linearly polarized light at the input of the FLC cell and the cell’s optical axis exhibit an angle of 45°. Hence, the FLC cell rotates the linearly polarized input light by 90°. In the off-state the polarization direction and the optical axis of the cell are parallel (lower part of figure 1 (b)), which causes the light to be transmitted without its polarization state being affected by the FLC cell. The second $\lambda/4$-plate subsequently reconverts the light into left- or right-handed circularly polarized light depending on the switching state of the FLC cell. Finally, this light is either transmitted or reflected by the second cholesteric filter.

In the blocking state (lower part of figure 1(b)) the combination of the three optical elements $\lambda/4$-plate / FLC cell / $\lambda/4$-plate acts as an achromatic $\lambda/2$-plate which is quite insensitive to variations of the optical retardation of its constituents. This important feature is responsible for the fact that the dark state, which determines the contrast ratio of the color switch, is not susceptible to variations of the optical retardation of its parts. In the transmitting state of the BMF the optical retardations of the two $\lambda/4$-plates and the FLC switch should precisely compensate each other. Fluctuations of their respective retardations may deteriorate the bright-state transmission of the BMF. However, because the color purity of our BMF color switch is basically determined by the light leakage of the dark states of its BMF modules this is not critical either. Because of the BMF color switch’s excellent level of transmission, a slight reduction of the bright-state transmission caused by deviations from the ideal optical retardations of its optical components is tolerable.

Outside the selective wavelength band of a BMF the light is not affected and maintains its initial unpolarized state. The three BMF modules which make up the complete BMF color switch are nevertheless not optically independent of each other. Each circularly polarized color component generated by a preceding BMF module will experience a rotation of its handedness after passing through a subsequent BMF module (due to traversing the achromatic $\lambda/2$-plate composed of $\lambda/4$-plate / FLC switch / $\lambda/4$-plate). Since the three primary colors should preferably exit the BMF color switch in the same state of polarization, means have to be provided to achieve this goal.

We have solved the equal output polarization problem in our BMF configuration by choosing oppositely handed cholesteric filters for the green, central BMF module (figure 1(a)). An interesting additional benefit from this design is that it enables building electronic BMF color switches with arbitrarily overlapping wavelength bands as well as with gaps between the bands. As outlined above, this allows independent optimization of transmission and color gamut of BMF color switches.
By computer simulations based on the 4x4 matrix formalism [8] we optimized the properties of our BMFs with the objective to achieve an electronic color switch with maximum brightness and with color coordinates meeting NTSC standards. The results are shown in figures 2 and 3 which demonstrate that the BMF color switch exhibits almost ideal light transmission for the three primary colors and its chromaticity indeed matches NTSC standards. These results illustrate the importance of the concept of overlapping blue and green wavelength bands. The calculations were made assuming uniform input light intensity over the visible spectral range. A similar optimization procedure can be performed taking the spectrum of a realistic light source into account. This enables adapting the optical performance of BMF color switches to specific light sources and thus achieving optimum overall performance. Moreover, our simulations show that for all f-numbers larger than 2.6 color shifts of less than 0.01 occur for all three color coordinates, i.e. non-vertically incident input light does not degrade color switch performance.

3. Experimental Results

We have built a prototype of a BMF color switch based on our novel optical design. The liquid crystal polymer (LCP) materials for the thin-film retarders and cholesteric filters are made by ROLIC. All LCP thin-films as well as the FLC cells are LPP-photo-aligned [7,9]. Our LPP/LCP technology enables a favorable stacking of optical retarders and cholesteric filters thus avoiding lamination. Since the total thickness of all optical thin-films is less than 150 µm, the thickness of a complete BMF color switch is essentially determined by the thickness of the three FLC cells. Our thermally and optically highly stable [7] photo-aligned cholesteric filters and retarders reach polarization contrast ratios exceeding 200:1. Deformed helix ferroelectric (DHF) cells [10] are used as FLC cells which are also LPP-photo-aligned [11,12]. Bistable surface stabilized ferroelectric (SSF) FLC cells [13] can be used as well. Figure 4 depicts the transmission spectra of our BMF color switch and figure 5 shows its color coordinates. The excellent chromaticity fits the above simulations well. Compared with our former BMFs the transmission of our new BMF color switch is markedly improved [4]. Its overall transmission is approximately 35%. The decline of transmission at short wavelengths during the blue frame time is caused by a DHF cell whose birefringence deviates from the value assumed in our calculations. The spectra in figure 4 clearly show the important overlap of the blue and green wavelength bands and the gap between the green and red bands. Our present prototype does not yet comprise antireflection coatings. Moreover, additional losses occur due to reflections at internal interfaces (ITO/glass and ITO/FLC) as well as by imperfect matching of the λ/4-plates and the DHF cells. When correcting for these losses, we expect the overall transmission of BMF color switches to exceed 40% for unpolarized input light. Since our electronic BMF color switch simultaneously acts as a non-absorbing, broadband polarizer which renders pre-polarizers in projectors redundant, its high transmission can be compared with that of state of the art linear sheet polarizers.

4. Conclusion

We present a new electro-optical concept for a fast responding, bright, electronic band modulation color shutter which acts as a non-absorbing broadband polarizer and is characterized by: integrated, non-absorbing liquid crystal polymer optical thin-film elements with excellent light and thermal stability, a broad color gamut, the feasibility of polarization recovery and response times well below 100 µs at 15 V driving voltage applying ferroelectric liquid crystal shutters. Moreover, our BMF color shutter enables arbitrarily and independently adjustable selective wavelength bands. A low number of thin-film coating steps are required in production. A prototype of our novel RGB color switch will be presented at the conference.
5. References