Invited Paper

Optical characteristics of wavelength-optimized reflective FLC SLMs

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ABSTRACT

We demonstrate that with a single manufacturing process and custom FLC materials, individual reflective FLC SLMs can be optimized for a wide range of chosen wavelength regions. One lot of 256 × 256 SLM cells were prepared from a single silicon wafer. These cells were filled with five different FLC materials having birefringence spanning a range from 0.129 to 0.218. The resulting retardance variation allowed SLM characteristics to be tailored to give optimized performance in any wavelength region from 400nm to 1000nm.

Keywords: spatial light modulator, ferroelectric liquid crystal, polarization modulator, wavelength optimization

1. Introduction

We have found that process changes associated with increasing our SLM manufacturing capacity also result in improved SLM performance. Specifically, we have fabricated 256 × 256 SLMs with diffractive zero-order throughputs above 45%, rise/fall times of less than 75μs, and most importantly, contrast ratios of a few thousand to one. This reported contrast ratio is most significant since it represents an order of magnitude increase over contrast ratios previously reported.[1,2] Process refinement has also enhanced uniformity in the FLC layer thickness for such devices, thus providing uniform half-wave retardance over the active area. With our reflective FLC SLM devices the retardance Γ is a function of two properties, the birefringence Δn of the FLC material and the FLC layer thickness d given in equation 1:

$$\Gamma = \Delta n d. \tag{1}$$

FLC layer thickness effects the overall retardance of the active area in a given device from a topography standpoint. Consequently, if the layer spacing varies over the active area of a specific device, the retardance and hence device performance will also vary over this active region. The birefringence value of the employed FLC material determines the wavelength dependence for any given device. Assuming the FLC layer thickness is constant, the birefringence properties of the FLC material dictate the most useful wavelength region of the SLM. We demonstrate the ability to finely tune standard batch processed devices by selecting the appropriate FLC material to achieve operation in a desired wavelength region. In developing thousands of unique FLC mixtures, we are able to control wavelength performance over a broad spectrum. Although FLC material qualities such as switching speed, tilt angle and transition temperatures are important, the materials listed in Table 1 were chosen specifically for their birefringence values:

Liquid Crystal Type	Δn at 589nm
MX8226	0.129
MX8068	0.138
MX8575	0.158
MX8265	0.177
MX8604	0.218

Table 1

The FLC materials listed in Table 1 were placed in transmissive, 1.8μm spaced cells for initial evaluation of optical throughput vs. wavelength. The sample FLC cells were placed between crossed broadband polarizers and aligned for uniform extinction under a constant applied electric field. Effects on performance caused by differences in material birefringence are shown in Figure 1.

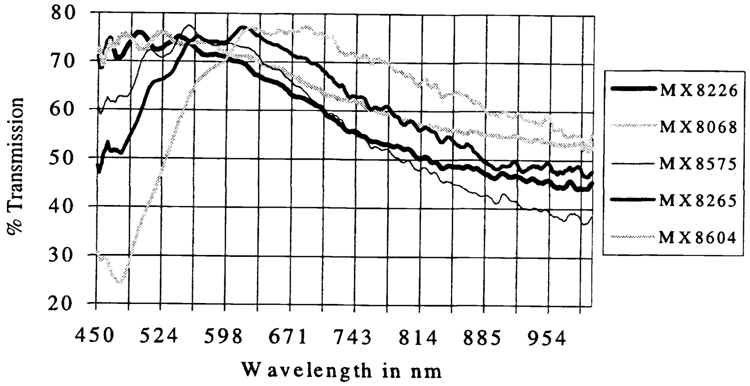

Figure 1: FLC material dispersion effects on optimized wavelength performance for 1.8 μm spaced transmissive cells

As the birefringence value of the FLC material increases, the wavelength region with highest optical efficiency moves towards the near infrared (NIR). Although these effects tail off as wavelength increases through the NIR region, it is demonstrated that the birefringence of a given FLC material has a definite effect on shifting the wavelength region of maximum efficiency.

Transmissive cells, such as those employed above, comprise two thin glass plates which bear indium tin oxide (ITO) coatings on the inner surfaces. The FLC material is sandwiched between these glass plates. ITO coating allows for the application of the electric field required for polarization modulation. With the SLMs described later, a silicon integrated circuit with reflective aluminum pixel pads is substituted for one of the glass plates. The interference between light reflected from the aluminum electrode/mirror surface and from the ITO coating within this cell causes device throughput to vary with wavelength in a way different from that found in a transmissive cell. Figure 1 demonstrates the principal effect on optical efficiency of the FLC material birefringence. The reflective FLC SLM's optical efficiency will also be influenced by the interference effects mentioned above. To isolate the effect of this interference, an empty SLM device was filled with 4-bromoanisole, an optically isotropic liquid of refractive index 1.563. Figure 2 demonstrates the broad band optical throughput of such a device when placed between parallel polarizers.

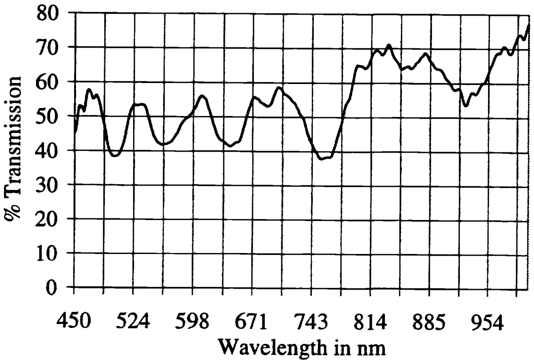

Figure 2: Reflective SLM filled with 4-bromoanisole with a refractive index n of 1.563

Figure 2 shows that, unlike the transmissive devices which have an optical throughput that varies smoothly with wavelength, the throughput of the reflective SLMs exhibits more closely spaced spectral features, in spite of the planarized CMOS process used to fabricate the backplane. The SLMs filled with actual FLC also evidence these spectral features, complicating the interpretation of optimum wavelength band.

2. Procedure

Nominally identical 256 x 256 SLM die were filled with the five FLC materials listed in Table 1. After filling, they were carried through standard die attaching, bonding and encapsulation processes. Finished devices were tested in the set up shown in Figure 3:

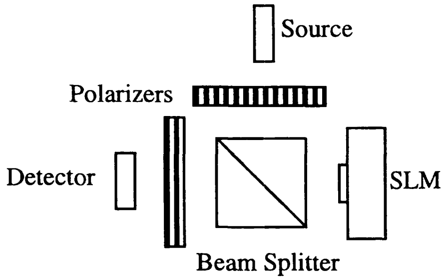

Figure 3: Test setup used for SLM ON and OFF measurements

The illumination source is a collimated tungsten-halogen beam, which passes through a broad band linear polarizer. The beam splitter is a nonpolarizing cube. After reflection off the SLM surface, the light exits through a crossed analyzer and is read into the detector for our fiber-optic spectrophotometer system. The collimated input beam is sized to just fill the active area of the SLM. The SLMs under evaluation were driven with consecutive all ON and all OFF frames, with the SLM being aligned for maximum extinction when held in the OFF state.

Similar to the operation of a FLC shutter[3], when these devices are aligned for a maximum OFF state this state is achromatic. The OFF values for individual SLMs tested were measured to ensure that the devices exhibited a minimum 100:1 contrast ratio. One such contrast graph is shown below in Figure 4.

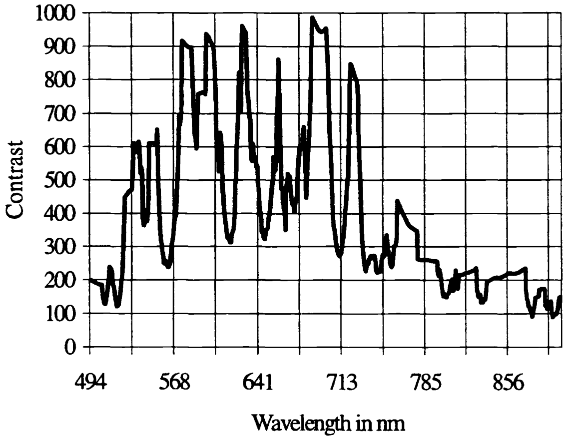

Figure 4: Contrast ratios for a typical measured SLM device over a broad wavelength region

Because we can achieve an achromatic and consistent OFF state, this paper analyzes the variations in ON state SLM transmissions. Although the contrast ratio values listed in Figure 4 are above the 100:1 level throughout the listed spectrum, variations in specific device transmission will affect to what extent contrast ratios can be maximized.

3. Results

Within the five groups of SLMs that are presented in this paper, the number of individual devices per group varies slightly. Either four or five SLMs from each FLC material group are presented.

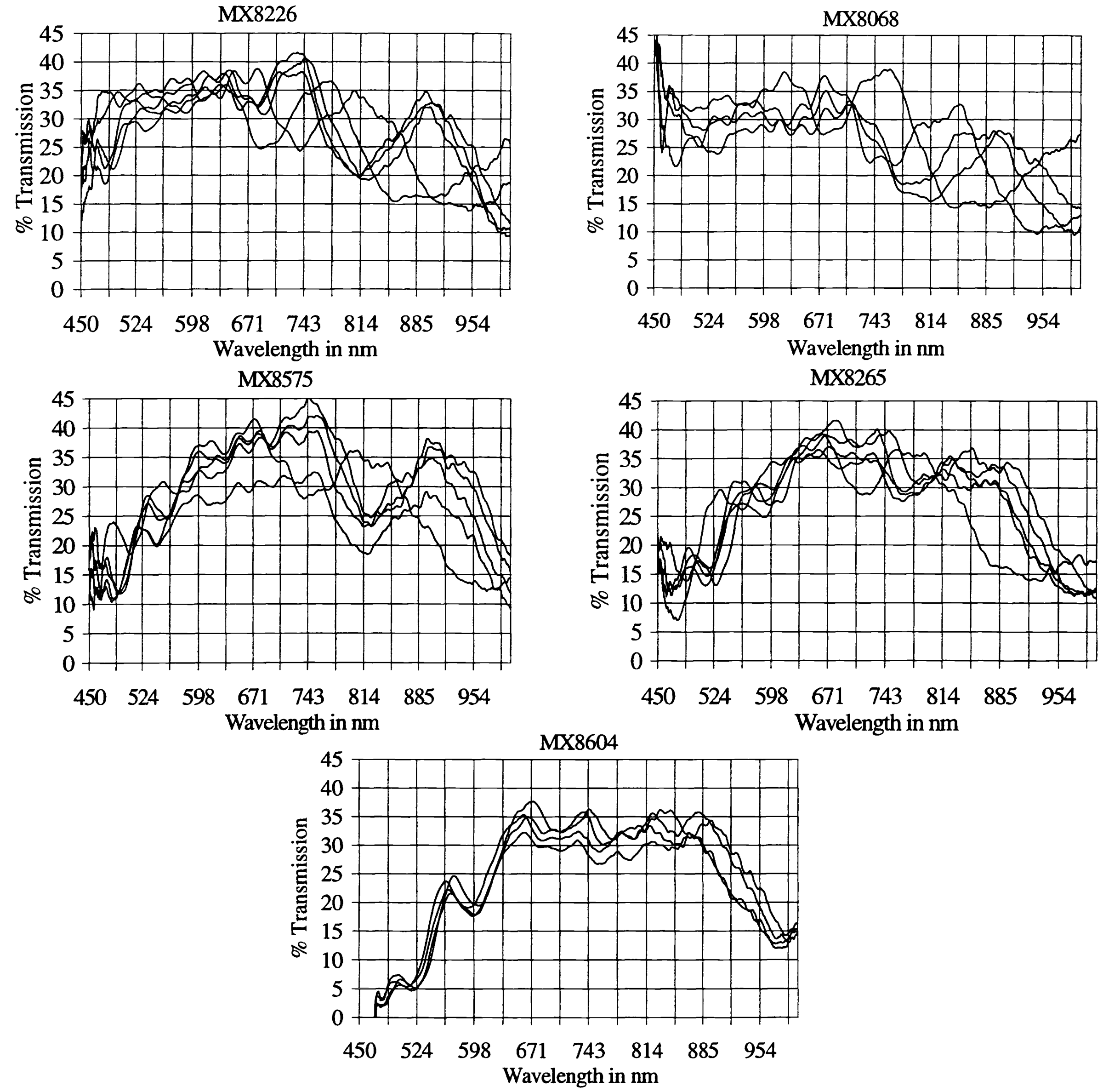

Figure 5: Graphs of SLM percent transmission versus wavelength for the five groups of FLC materials tested

The five graphs shown in Figure 5 demonstrate the optimized operational wavelength region for each group of SLMs. All of the SLMs which are present in Figure 5 meet the minimum quoted performance requirements of 25% throughput, and a 100:1 contrast ratio over a given wavelength region in the spectrum shown. Differences in the optimized wavelength region are clearly present for these five graphs.

4. Discussion

From the graphs in Figure 5, it is demonstrated that the optimized wavelength region generally moves towards the NIR with increasing birefringence of the FLC material utilized. Although the variation in device performance within each material group can be seen from in Figure 5, the graph in Figure 6 compares the optimized wavelength region for each of the five FLC materials tested. The bars shown highlight only the region where all listed SLMs are within our standard specifications, namely, a zero order diffraction efficiency of greater than 25%, and a contrast ratio of greater than 100:1. From the graphs in Figure 5, there are devices that will pass the listed criteria and fall outside the optimization bars from Figure 6. Figure 6 is not intended to show what can be possible with hand selection of devices, but rather the minimum wavelength region that is acceptable and common to all of the tested devices within each of the five FLC material groups shown.

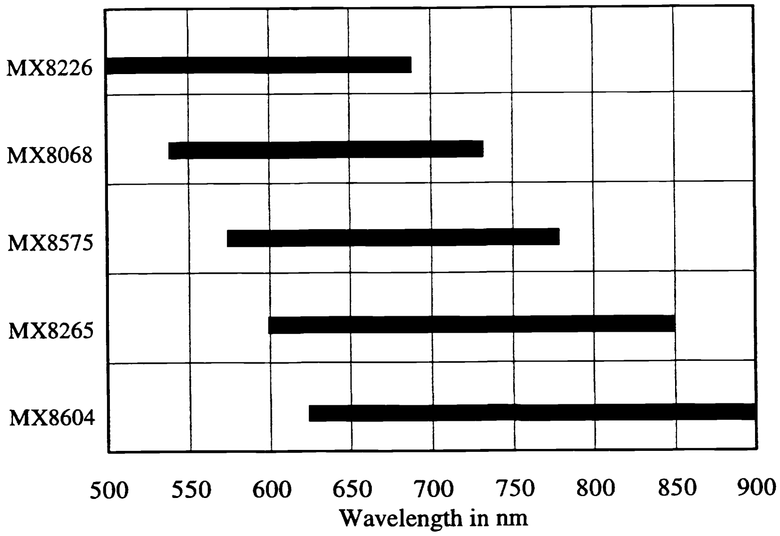

Figure 6: Comparison of the optimized wavelength region for the five FLC materials tested

5. Conclusion

It is demonstrated that by changing the FLC material used in individual 256 × 256 reflective SLM devices, that repetitive wavelength optimization is possible. This is significant because batch processing can be coupled with custom FLC materials to produce wavelength-optimized devices of superior quality.

It should be noted that the stated 400 – 1000nm wavelength range was primarily defined by the capabilities of commonly used measurement equipment. It is expected that optimized operation above the stated wavelength region is also possible.

6. References

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