Achromatic ferroelectric liquid crystal polarization rotator

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ABSTRACT

The ability to accurately rotate the polarization of incident light while minimizing any losses in polarization purity has applications in optical switching, polarimetry, and microscopy. Polarization rotators utilizing tunable birefringent plates, such as liquid crystal (LC) devices, have the advantage of non-mechanically tuning the devices' retardance. However, these devices properly work with incident light within a very specific wavelength range. Ferroelectric liquid crystal (FLC) devices can switch between two orthogonal states of linear polarization, and offer response times much faster than their nematic liquid crystal cell counterparts. An achromatic polarization rotator can be constructed with an FLC cell between two half-wave plates that have been constructed to produce a half-wave retardance at a certain design wavelength. This results in a device that offers fast response times and high polarization purity over a broader wavelength range.

Keywords: FLC, polarization rotator, liquid crystal, polarimetry

1. INTRODUCTION

Polarization modulators are critical components to polarimetric imaging systems. These modulators can change the orientation of linearly polarized incident light using mechanical techniques, or by using variable retarders that either change the birefringence or fast axis of the retarder. The device we present here is an achromatic ferroelectric liquid crystal (AFLC) polarization rotator capable of rotating linearly polarized incident light by 90° over a broad wavelength range, and can outperform standard liquid crystal devices with faster response times less than $100\mu s$.

2. FERROELECTRIC LIQUID CRYSTAL RETARDERS

The ferroelectric properties of the chiral smectic C phase (SmC*) was first predicted in 1975.[1] The key element of the AFLC device is the ferroelectric liquid crystal modulator, which acts as a bistable, switchable half-wave plate. The FLC modulator's most significant advantage over other polarization modulators, namely nematic LC modulators, is their fast response times, which are typically less than $100\mu s$ (dependent on the device's thickness, material, and temperature). Nematic LC modulators have typical response times on the order of ms. Ferroelectric liquid crystals possess a spontaneous polarization that interacts directly with the applied electric field,[2] and is not subject to the relaxation forces that limit the response time of nematic LC devices. Although it has been recently demonstrated that nematic liquid crystal devices can achieve sub-millisecond response times, these devices require high applied voltages ($\approx 100V$[3]), external lasers[4] , or complex methods for preparation and construction[5] . As a result, these add undesired costs and complexity to experimental setups and devices that would potentially incorporated these sub-millisecond nematic LC modulators.

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3. ACHROMATIC DESIGN

The optimal performance for a single FLC occurs when operated at a specific wavelength[6] . The AFLC device's design is, in general, based on design criteria first presented by Pancharatnam[7] . He showed that the resulting stack's retardance 2δ is related to other parameters of the stack by

$$\cos\delta = \cos 2\delta_1 - \sin 2\delta_1 \sin\delta_2 \cos 2c, \tag{1}$$

where $2\delta_1$ is the retardation of the first and third plate, $2\delta_2$ is the retardation of the central plate, and c is the angle between the fast axis direction of the central plate and the other two. The stack's fast axis c_1 is given by

$$\cot 2c_1 = \csc 2c(\sin 2\delta_1 \cot\delta_2 + \cos 2\delta_1 \cos 2c). \tag{2}$$

Suitable choice of δ_1, δ_2 and c will achieve achromaticity of the stack characterized by:

- the desired retardance 2Δ in the vicinity of the design wavelength λ_0 at which the plate retardances are measured,
- a dimensionless constant f such that the stack retardance is equal to the desired retardance 2Δ at the two wavelengths $\lambda_0/(1+f)$ and $\lambda_0/(1-f)$,
- the fast axis orientation angles of the stack being equal (to each other) at these two wavelengths.

Assuming constant birefringence as a function of wavelength, Pancharatnam derives the following using Poincaré sphere considerations for which he credits F. Pockels[8] :

- $2\delta_1$ is, for non-half-wave (HW) achromats ($2\Delta \neq \pi$), the implicit solution of the transcendental equation

$$\sin(f \cdot 2\delta_1) = \frac{\sin(f \cdot \frac{\pi}{2})}{\cos\Delta} \sin 2\delta_1 \tag{3}$$

  whereas for HW achromats ($2\Delta = \pi$), we have $2\delta_1 = \pi$, i.e. the outer plates are half wave retarders at the design wavelength λ_0.
- $2\delta_2 = \pi$, i.e. the center plate has half wave retardance at the design wavelength λ_0 for both HW and non-HW achromats.
- The center plate must have a rotation angle c relative to the outer plates that solves the equation:

$$\cos 2c = -\frac{\tan(f \cdot \frac{\pi}{2})}{\tan(f \cdot 2\delta_1)}. \tag{4}$$

Pancharatnam's design criteria also applies to switchable waveplates. This application was further developed by Hariharan and Ciddor[9] , and it is their work that the AFLC design is based on. The system is shown in Figure 1, with the 3-stack AFLC device between crossed polarizers. In Figure 1, the FLC is between two

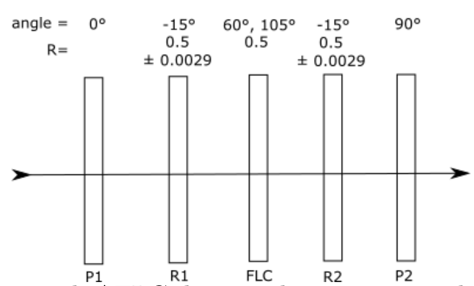

Figure 1: 3-stack AFLC diagram between crossed polarizers.

half-wave plates with their fast axes parallel at -15° w.r.t. the input polarizer, P1. Initially, the fast axis of the FLC is 60° w.r.t. P1. When voltage is applied to the FLC, its fast axis switches to its other bistable state. We've measured a switching angle of approximately 43°.

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4. ACHROMATIC FLC ROTATOR DEVICE

4.1 Mechanical design

The AFLC is enclosed in a 2 inch diameter, anodized-black aluminum housing. The device is 1.38 inches thick, and has a 0.80 inch mechanical clear aperture. Figure 2 is an illustration of the AFLC components. The device can be mounted using an appropriate post, and by using other opto-mechanical components. Further development includes offering different sizes of the device.

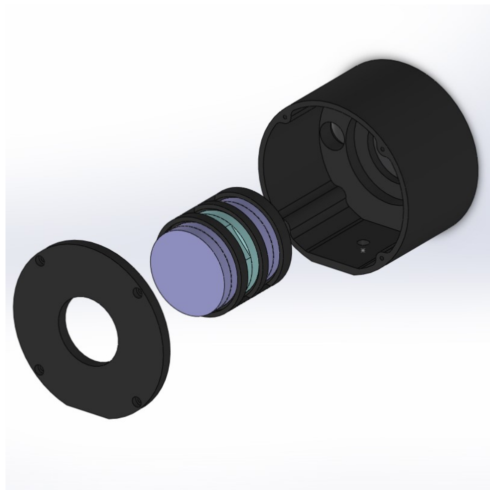

Figure 2: Illustration of the AFLC and its componenets

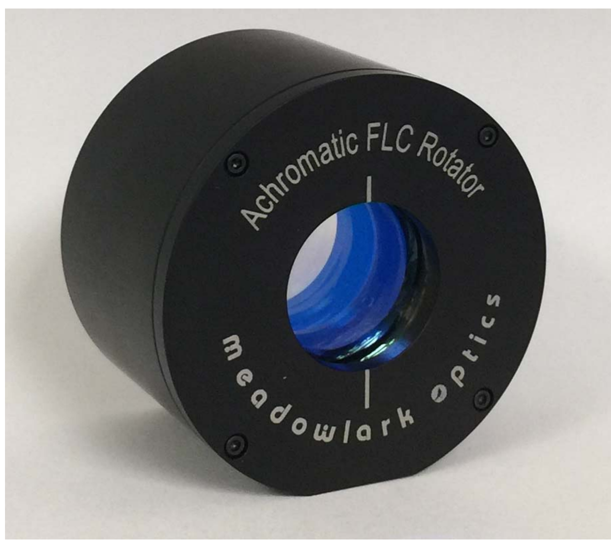

Figure 3: Meadowlark's AFLC Rotator

4.2 Optical components

Figure 4 shows a diagram of the optical subassembly of the AFLC. The fast axes of each of the optical components are aligned as shown in Figure 1, but are optimized during construction by monitoring the transmission of the devices (both open and closed states) in situ. The half-wave plates are true zero order retarders consisting of a birefringent polymer cemented between two BK-7 windows. The FLC cell is also a true zero order switchable half-wave retarder, and as mentioned in section 3, has a switching angle of approximately 43°.

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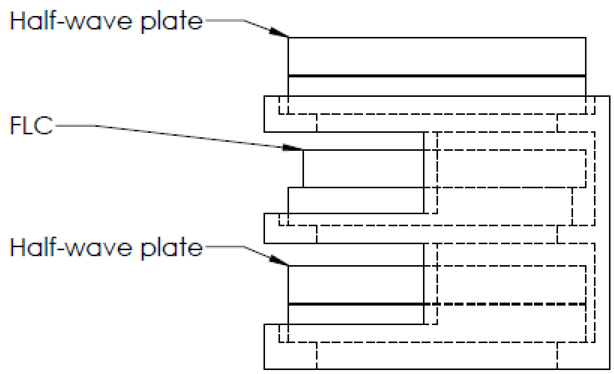

Figure 4: Optical subassembly diagram.

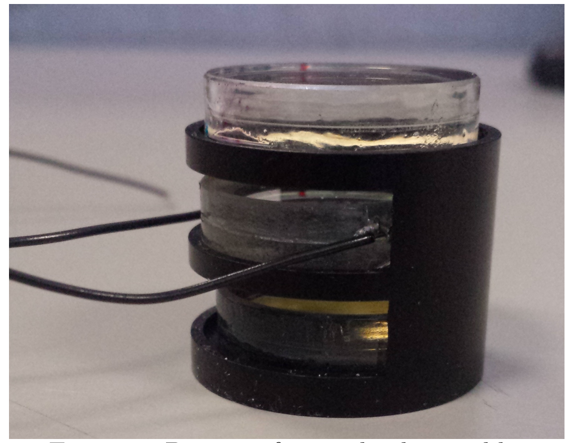

Figure 5: Picture of optical subassembly.

4.3 Operation

The AFLC requires a DC-balanaced AC drive signal, typically resulting in a 50% duty cycle operation. Meadowlark Optics also offers a controller specifically designed to drive ferroelectric liquid crystal modulators.

4.4 Theoretical transmission model

For the AFLC device we're presenting here, and the mechanical dimensions given above, our AFLC has a maximum angle of incidence of 24.9°. Figures 6 and 7 are theoretical curves for the open and closed states for polarized light at normal (0°) incidence, and 24.9°.

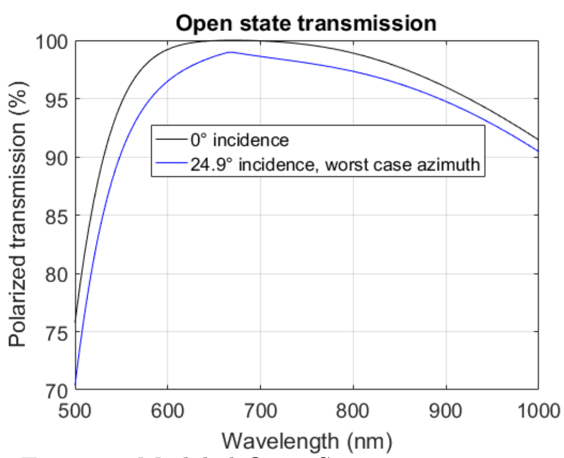

Figure 6: Modeled Open State transmission.

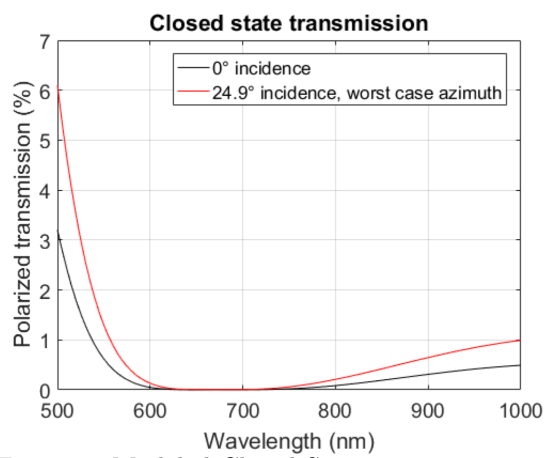

Figure 7: Modeled Closed State transmission.

4.5 Data

Measured data for two AFLC's are shown in Figures 8 and 9. AFLC-1 consists of an FLC and two half-wave plates, all with a design wavelength of 670nm. AFLC-2 consists of an FLC and two half-wave plates, all with a design wavelength of 633nm.

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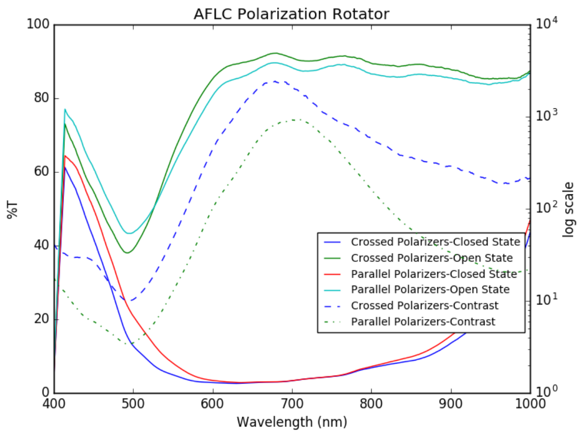

Figure 8: Measured data for AFLC-1.

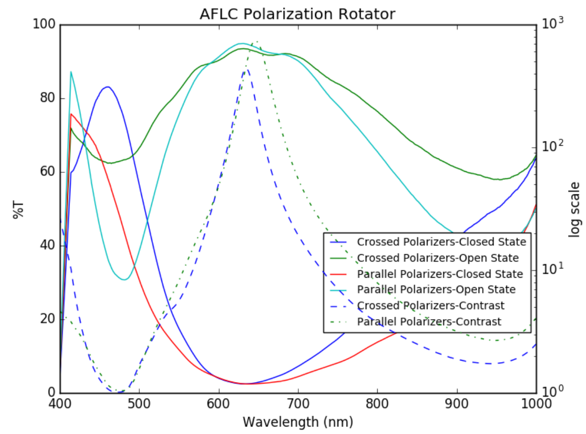

Figure 9: Measured data for AFLC-2.

Figures 10 and 11 are contrast ratio plots for AFLC-1 and AFLC-2, resp. These plots compare the contrast ratio of a single FLC, and the resulting AFLC (these can be thought of as *before* and *after* plots of the FLC). In both devices, we are able to demonstrate and increase in the FLC's wavelength range and contrast ratio.

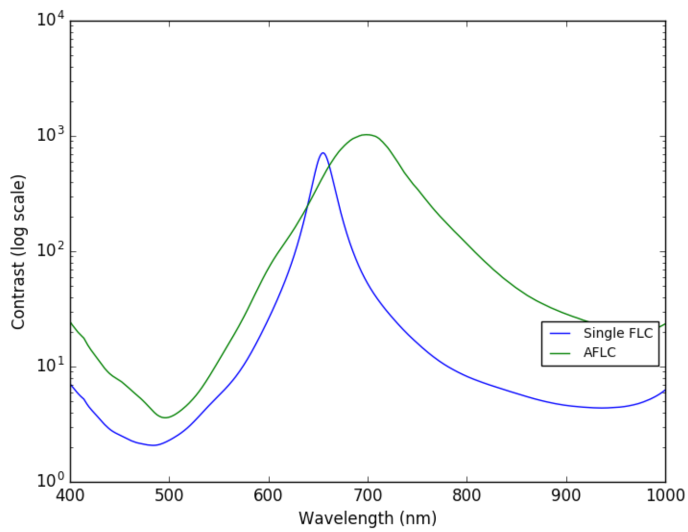

Figure 10: Contrast Comparison, Single FLC and AFLC-1.

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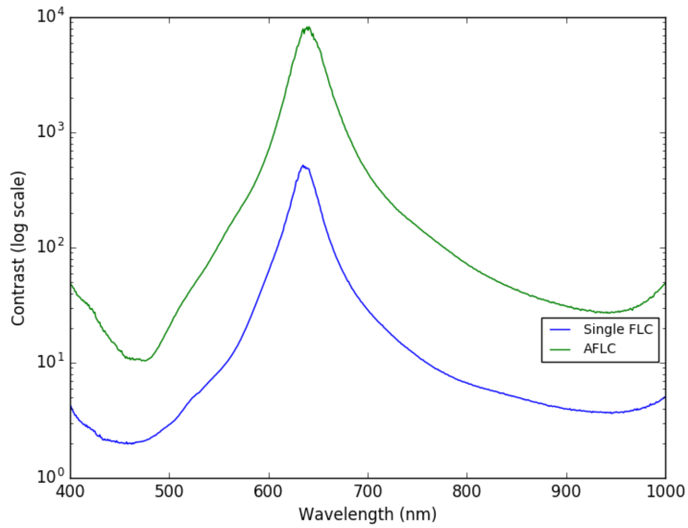

Figure 11: Contrast Comparison, Single FLC and AFLC-2.

Figures 12 and 13 are response times for AFLC-1 (response times are similar for AFLC-2). Figure 14 is data of the AFLC operating at 1kHz.

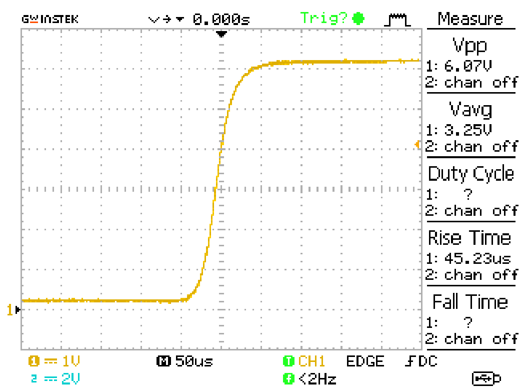

Figure 12: Rise Time, AFLC-1

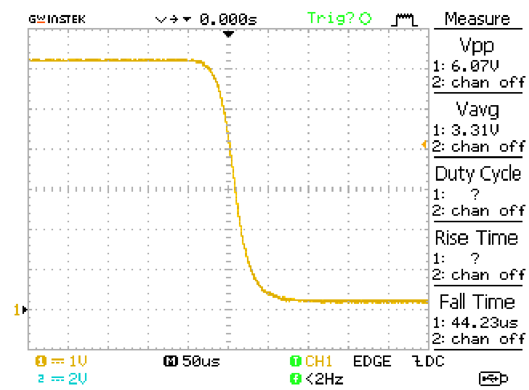

Figure 13: Fall Time, AFLC-1

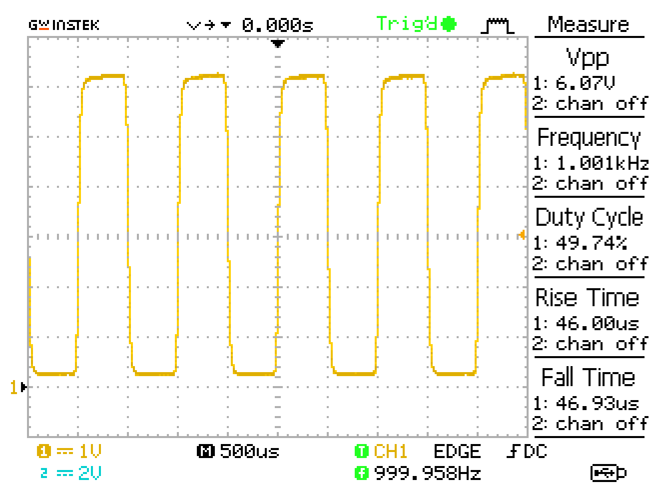

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Figure 14: AFLC-1, kHz operation.

4.6 Conclusions

We have presented a single packaged achromatic polarization rotator capable of response times $< 100\mu s$, and contrast ratio of at least 200 : 1 over a broad range around the single FLC's design wavelength. The wavelength dependence of the FLC is overcome by placing it between two half-wave plates and by strategically orienting their fast axes. Future development work for this device includes investigating temperature dependence, building devices to cover different wavelength ranges, and different mechanical sizes. The most direct application for this device is in polarimetric imaging, which requires fast polarization modulation in the kHz range to avoid errors due to the turbulence of the Earth's atmosphere. Other electro-optical modulators can be used to achieve this fast polarization modulation, but there usefulness is still limited by their wavelength dependence on their performance.[10] Though other achromatic rotators can be constructed, our AFLC device is already aligned, housed, and ready for use. An example of where others have constructed their own achromatic polarization rotator is The Zurich Imaging Polarimeter (ZIMPOL), operated at the Institute of Astronomy of the ETH in Zurich. Their polarimeter uses a single FLC modulator in combination with a zero order half-wave plate to reduce the FLC modulators chromatic effects.[11]

REFERENCES

[1] Meyer, R. B., Liebert, L., Strzelecki, L., and Keller, P., "Ferroelectric liquid crystals," *Journal de Physique Lettres* **36**(3), 69–71 (1975).

[2] MacGregor, A. R., "Method for computing the optical properties of a smectic c* liquid-crystal cell," *JOSA A* **6**(9), 1493–1503 (1989).

[3] Borshch, V., Shiyanovskii, S. V., and Lavrentovich, O. D., "Nanosecond electro-optic switching of a liquid crystal," *Physical review letters* **111**(10), 107802 (2013).

[4] Cattaneo, L., Savoini, M., Muševič, I., Kimel, A., and Rasing, T., "Ultrafast all-optical response of a nematic liquid crystal," *Optics express* **23**(11), 14010–14017 (2015).

[5] Xiang, J. and Lavrentovich, O. D., "Blue-phase-polymer-templated nematic with sub-millisecond broad-temperature range electro-optic switching," *Applied Physics Letters* **103**(5), 051112 (2013).

[6] Kraemer, M. and Baur, T., "Achromatic devices in polarization optics," in [*Optical Components and Materials XV*], **10528**, 105281C, International Society for Optics and Photonics (2018).

[7] Pancharatnam, S., "Achromatic combinations of birefringent plates," in [*Proceedings of the Indian Academy of Sciences-Section A*], **41**(4), 130–136, Springer (1955).

[8] Pockels, F. C. A., [*Lehrbuch der kristalloptik*], vol. 19, BG Teubner (1906).

[9] Hariharan, P. and Ciddor, P. E., "Achromatic switchable polarization rotators," *Optical Engineering* **36**(3), 952–956 (1997).

[10] Gisler, D., Feller, A., and Gandorfer, A. M., "Achromatic liquid crystal polarization modulator," in [*Polarimetry in Astronomy*], **4843**, 45–55, International Society for Optics and Photonics (2003).

[11] Roelfsema, R., Schmid, H. M., Pragt, J., Gisler, D., Waters, R., Bazzon, A., Baruffolo, A., Beuzit, J.-L., Boccaletti, A., Charton, J., et al., "The zimpol high-contrast imaging polarimeter for sphere: design, manufacturing, and testing," in [*Ground-based and Airborne Instrumentation for Astronomy III*], **7735**, 77354B, International Society for Optics and Photonics (2010).

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