COSMO Large Coronagraph Tunable Filter Design and Development

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1 INTRODUCTION

The last two decades have seen increasing interest in large scale synoptic surveys in astronomy (Tyson 2010) for the study of time domain astrophysics, spurred by advances in detector technology. Closer to home, society continues to become increasingly dependent on critical assets which are vulnerable to the Sun’s highly variable output of particles, radiation and magnetized plasma. These solar influences impact the earth and its environment and are collectively known as space weather. The increasing relevance of space weather necessitates the continuous synoptic monitoring of solar outputs and motivates progress towards understanding the causes of space weather.

While the physical mechanisms are still under study, it is clear that the underlying cause of most solar eruptions involves the storage and release of magnetic free energy in the million-degree solar corona. Magnetism dominates the force balance in the corona. Despite this fact, few measurements of the strength and direction of the coronal magnetic field exist. The Coronal Solar Magnetism Observatory (COSMO; reference) is a proposed ground-based facility designed to address the shortfall in our capability to measure magnetic fields in the solar corona. At its heart is the 1.5m aperture Large Coronagraph (LC) which will synoptically observe the polarized radiation emitted by the corona in a number of visible and near-IR emission lines. A post-focus narrow-band tunable filter and polarimeter will analyze the circular and linear polarization signals induced by the Zeeman and saturated Hanle effects, allowing us to infer the strength and direction of coronal magnetic fields.

The LC employs an innovative refractive design to obtain measurements over a 1° field-of-view (FOV) at a spatial resolution of 2 arcseconds with high spectral resolution. Measuring coronal magnetic field strengths of order 1 Gauss over features that can subtend more than a solar radius drives the aperture and FOV requirements of the LC. The product of the solid angle of the FOV and the area of the entrance pupil is called the étendue (Jacquinot, 1954; also called luminosity) which quantifies the light gathering power of an optical system. It is therefore an important metric of any optical system, especially one that observes a large FOV with a large aperture telescope. To avoid light losses, the étendue must be conserved throughout the optical system. This places challenging requirements on the LC tunable filter which must accept the large étendue of the LC telescope while maintaining a spectral resolution which is on order of the width of the coronal emission lines it will observe.

In this paper we describe the development of high étendue tunable birefringent filters to be used as post-focus instrumentation behind the COSMO LC. In section 2, we develop the requirements for the LC tunable filter, and justify the selection of birefringent filters based on Lithium Niobate (LN) crystals. In section 3 we develop requirements for birefringence uniformity of LN crystals and show measurements of a sample of crystals. In section 4, we evaluate tuning LN crystals with high voltages, and measure the speed of LN crystal tuning. We conclude in section 5.

2 COSMO LC TUNABLE FILTER REQUIREMENTS

Along with étendue, an equally important quality of an optical system is its spectral resolution, \( R = \frac{\lambda}{\Delta \lambda} \), with the product of étendue and resolution providing a fundamental metric. For the COSMO LC, the spectral resolution requirement is set by the linear and circular polarization signatures in the coronal emission lines it observes. The LC will observe emission lines sequentially over a wavelength range between 530 and 1100 nm. Over this range, the linear polarization is due to the saturated Hanle effect and the profile is proportional to the intensity; both are approximately Gaussian with wavelength. The line width is due to broadening by the temperature of the coronal plasma associated with the emission line, plus additional broadening due to non-thermal effects. Then for linear polarization measurements, the signal can be integrated over the line profile and the spectral resolution element does not need to be as narrow as the emission line. However, the circular polarization profile due to the Zeeman effect is proportional to the derivative of the intensity profile. The profile is anti-symmetric with opposite senses of circu-
lar polarization present in the wings of the emission line. It is then the Zeeman observations that set the minimum spectral resolution which simulations show (Tomczyk et al., 1995) is approximately the e-folding half width of the emission line. Lower spectral resolution will allow the opposite circular polarizations to cancel and reduce the signal.

Figure 1 shows the minimum required resolution to observe a sample of the target emission lines for the COSMO LC as a function of wavelength. Each line is emitted from a particular ion at a characteristic plasma temperature. These lines span the temperature range from 0.1 to 4.4 MK. The resolution was computed by setting the $\Delta \lambda$ to the e-folding half width of the emission line, which was computed as the root-sum-of-squares of contributions from the thermal Doppler broadening, and a non-thermal contribution which was set to 30 km/s for all lines. Despite the large range in ion temperature and mass, the required spectral resolution has a very nearly constant value of $\sim$8000. This is due to the thermal broadening having a square-root dependence on the temperature and mass.

![Figure 1 - Dots - Minimum spectral resolution requirement for the COSMO LC coronal emission lines of interest. Solid line - Theoretical spectral resolution of a birefringent filter based on LN crystals as described in the text.](image)

We must estimate the étendue at the entrance aperture of the LC and require that the étendue of the filter exceeds that value so that the light gathering power of the optical system will not be compromised. The solid angle accepted by the telescope for a circular field is

$$\Omega = 4\pi \sin^2 \frac{\theta}{2} \text{ (sr)} \ ,$$

where $\theta$ is the half-angle (0.5° for the LC). Then for the LC, $\Omega = 2.39 \cdot 10^{-4}$ sr (0.785 deg$^2$) coupled with an entrance aperture area of 1.77 m$^2$ results in an étendue of 1.39 m$^2$deg$^2$. In comparison, the étendue of the 4m Daniel K. Inouye Solar Telescope (DKIST; Keil et al., 2003) with a 5 arc minute full FOV is 0.068 m$^2$deg$^2$, a factor of 20 less than the COSMO LC. The Large Synoptic Survey Telescope (LSST; www.lsst.org) will have an étendue of 320 m$^2$deg$^2$ which exceeds that of the LC by more than two orders of magnitude. Its enormous étendue is what makes the LSST extraordinary.

The challenge is to identify a spectrometer for the LC that can meet the spectral resolution requirement of 8000, and have an étendue that exceeds 1.39 m$^2$deg$^2$. The resulting étendue resolution product, E·R, requirement for the LC is $1.1 \cdot 10^4$ m$^2$deg$^2$. Jacquinot (1954) showed that Fabry-Perot spectrometers enjoyed an E·R advantage over prism and grating spectrometers by a factor between 30 and 400. Wide-field birefringent filters (Lyot, 1933; Evans, 1949) were shown to have a similarly large E·R advantage over Fabry-
Perot and Michelson interferometers (Title and Rosenberg, 1979) by a factor from 40 to 300. For this reason, and their wide usage in solar physics and other fields, we investigated whether wide-field birefringent filters could meet our E∙R requirement.

For a wide-field birefringent filter, the fractional wavelength shift as a function of the angle through the filter away from the normal, θ, is given to second order (Title and Rosenberg, 1979) by

\[ \frac{\Delta \lambda}{\lambda} = -\frac{1}{4n_o^2} \left( \frac{n_e - n_o}{n_e} \right) \sin^2 \theta, \]

where \( n_e \) and \( n_o \) are the extraordinary and ordinary indices of the material, respectively. For convenience, we denote the factor in front of the \( \sin^2 \theta \) term as \( F \), omitting the minus sign. The factor \( F \) then is a measure of the angular sensitivity of a birefringent filter, with a small value of \( F \) corresponding to low angular sensitivity. This occurs for filters that employ high index, low birefringence materials.

Assuming small angles so that \( \sin(x) \approx x \) (an excellent approximation for the angles considered here), and using the definition of spectral resolution, \( R = \lambda / \Delta \lambda \), we can combine equations [1] and [2] and derive an equation for \( E \cdot R \) of a birefringent filter,

\[ E \cdot R = \frac{\pi A}{F}, \]

where \( F = \frac{1}{4n_o^2} \left( \frac{n_e - n_o}{n_e} \right) \).

and \( A \) is the filter area. Then a birefringent filter can meet our requirements so long as birefringent materials can be found that meet the condition

\[ \frac{\pi A}{F} \geq E \cdot R \]

with \( E \cdot R = 1.1 \cdot 10^4 \) m²deg². Note that \( E \cdot R \) for a Fabry-Perot etalon is \( \pi A \) (Jacquinot, 1954), so comparison with equation 3 shows that the \( E \cdot R \) of a birefringent filter will exceed that of a Fabry-Perot etalon by a factor of \( 1/F \).

A search of the literature was conducted to identify crystals that could meet the \( \pi A/F \) requirement. The results of this search are shown in Table 1. The search identified five birefringent crystals that could meet the requirement. The crystal most commonly used in birefringent filters, calcite, suffers from the fact that it cannot be grown and is available in sizes only up to about 40 mm. This limited its \( \pi A/F \) to an unacceptable value of \( 1.2 \cdot 10^3 \) m²deg². The crystal with the highest \( \pi A/F \) was Magnesium Fluoride (MgF₂) owing to its availability in crystals of 120 mm size and its very low birefringence of 0.012. The birefringence is so low, however, that a MgF₂ birefringent filter able to meet the spectral resolution requirement would need to have crystals 605 mm in total length, and it was rejected for this reason. Quartz, which would require 807 mm total crystal length, was rejected for the same reason. The crystal that was selected was LN which has a refractive index around 2.2, a birefringence of 0.086 (about half that of calcite), and is commonly grown in diameters of 100 mm. This produces a \( \pi A/F \) of \( 4.5 \cdot 10^4 \) m²deg², which exceeds the requirement by a factor of \( \sim 4 \). The value of \( F \) for LN is \( 1.8 \cdot 10^{-3} \). For these reasons, LN has been used in high étendue birefringent filters (Staromlynska et al., 1998; Levinton and Yuh, 2008).
Table 1. List of birefringent crystals and their properties. The symbols for the properties are defined in the text. The length corresponds to the total length of crystal required to produce a filter of the required bandpass.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$n_o$</th>
<th>$n_c$</th>
<th>$n_c-n_o$</th>
<th>$F$</th>
<th>Diameter (mm)</th>
<th>$\pi A/F$ (m$^2$deg$^2$)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgF$_2$</td>
<td>1.384</td>
<td>1.396</td>
<td>0.012</td>
<td>1.12E-03</td>
<td>120</td>
<td>1.04E+05</td>
<td>605</td>
</tr>
<tr>
<td>LiNbO$_3$</td>
<td>2.286</td>
<td>2.203</td>
<td>-0.086</td>
<td>1.80E-03</td>
<td>100</td>
<td>4.49E+04</td>
<td>84</td>
</tr>
<tr>
<td>SiO$_2$ (quartz)</td>
<td>1.543</td>
<td>1.552</td>
<td>0.009</td>
<td>6.09E-04</td>
<td>50</td>
<td>3.33E+04</td>
<td>807</td>
</tr>
<tr>
<td>KDP</td>
<td>1.494</td>
<td>1.46</td>
<td>-0.034</td>
<td>2.61E-03</td>
<td>99</td>
<td>3.04E+04</td>
<td>214</td>
</tr>
<tr>
<td>TeO$_2$</td>
<td>2.26</td>
<td>2.142</td>
<td>-0.118</td>
<td>2.70E-03</td>
<td>50</td>
<td>7.51E+03</td>
<td>62</td>
</tr>
<tr>
<td>BaB$_2$O$_4$</td>
<td>1.658</td>
<td>1.584</td>
<td>-0.073</td>
<td>4.25E-03</td>
<td>50</td>
<td>4.77E+03</td>
<td>99</td>
</tr>
<tr>
<td>YVO$_4$</td>
<td>1.993</td>
<td>2.215</td>
<td>0.222</td>
<td>6.31E-03</td>
<td>38</td>
<td>1.85E+03</td>
<td>33</td>
</tr>
<tr>
<td>CaCO$_3$ (calcite)</td>
<td>1.656</td>
<td>1.485</td>
<td>-0.171</td>
<td>1.05E-02</td>
<td>40</td>
<td>1.23E+03</td>
<td>42</td>
</tr>
<tr>
<td>TiO$_2$ (rutile)</td>
<td>2.583</td>
<td>2.865</td>
<td>0.282</td>
<td>3.69E-03</td>
<td>25</td>
<td>1.37E+03</td>
<td>26</td>
</tr>
</tbody>
</table>

LN is widely used in optics due to its versatility; it is piezo-electric, ferro-electric, electro-optic, and non-linear. The fact that LN is an electro-optic material is valuable in this application in that it could be tuned in wavelength by the application of high voltage, relieving the need for liquid crystal variable retarders which are commonly used for this purpose. LN has been used for many years in electro-optically tuned Fabry-Perot etalons (Burton et al., 1987; Hernandez and Clark, 1994; Bonaccini and Smartt, 1988; Bayanna et al., 2014). Direct electro-optical tuning of LN may allow filter tuning much faster than liquid crystal retarders. Measurements of the speed of LC electro-optical tuning are reported in Section 4.

The LC filter spectral resolution requirements can be met with a 5 stage LN birefringent filter in a wide field configuration with the thickest stage comprised of two crystals 22 mm thick. Figure 2 is a schematic diagram of the components of the proposed LC tunable filter. The crystal thickness was selected to meet the resolution requirement at the FeXIII 1074 nm emission line. The FWHM resolution of the proposed LC birefringent filter is plotted in Figure 1 which shows the proposed filter exceeds the resolution requirement at all wavelengths. The increase in resolution towards shorter wavelengths is due to the crystal retardation being nearly constant in wavelength units making the bandpass decrease as 1/λ. The additional increase is due to dispersion of the birefringence of LN.
Figure 2 - Schematic diagram of the 5-stage birefringent filter. Not to scale. The polarizers and retarders are all oriented with their transmission and fast axes at 0 degrees, and the crystal pairs are oriented at 45 and -45 degrees.

3 Birefringence Uniformity of LN Crystals

The theoretical spectral resolution of a birefringent filter can only be achieved so long as the crystals have sufficiently uniform birefringence. The Free Spectral Range (FSR) of one stage of a birefringent filter is given by

$$\text{FSR} = \frac{\lambda^2}{\varepsilon d} \left( \frac{\lambda}{\varepsilon} \frac{\partial \varepsilon}{\partial \lambda} \right)^{-1}$$

(Evans, 1949). The term in brackets is due to the dispersion of the birefringence and modifies the computed value of the free spectral range by about 10% for visible and near-IR wavelengths (Title, 1974). We will neglect the bracketed term here. The full width at half-maximum (FWHM) of the transmission peak of a filter stage is equal to one half of the free spectral range. Then,

$$\text{FWHM} = \frac{\lambda^2}{2\varepsilon d}.$$  \hspace{1cm} (6)

Rearranging Eq. 6 and differentiating we obtain

$$\frac{\Delta \varepsilon}{\Delta \lambda} = \frac{\lambda}{\text{FWHM} d}.$$ \hspace{1cm} (7)

Note that this quantity is not the dispersion of the birefringence as in Equation 5, but represents the relationship between the change in birefringence with the change in peak transmission wavelength. The basic requirement is that the birefringence should be sufficiently uniform so that the wavelength of peak transmission varies by less than the FWHM/10. Imposing this constraint in Equation 7 gives

$$\Delta \varepsilon \leq \frac{\lambda}{10 d}.$$ \hspace{1cm} (8)

The form of Equation 8 indicates that the birefringence uniformity requirement will be easier to meet at higher wavelengths and for thinner crystals. A given degree of non-uniformity will tend to cause the spectral resolution to be poorer at shorter wavelengths. The baseline LC filter design exceeds the resolution requirement by more than a factor of two at shorter wavelengths, and some broadening would actually be tolerable. Since there are two crystals in each wide-field stage, the birefringence perturbations will add,
The birefringence uniformity specification of Equation 8 needs to be tightened by a factor of $\sqrt{2}$. The 22 mm LN crystals used in the thickest wide field stage requires the birefringence to be uniform to $3.5 \cdot 10^{-6}$ at 1074 nm.

To evaluate the quality of commercially available crystals, we obtained 44 crystals from four different vendors, in thicknesses ranging from 0.5 to 25 mm, and diameters between 75 and 100 mm. The crystals were polished to be flat and without wedge. We built an experimental set-up where a LED light source near 635 nm is collimated and passed through the crystal under test which sits on an x-y stage. An iris isolates a 1 mm diameter area on the crystal and the light passing through the iris is focused on an optical fiber and input into a spectrograph. The crystal is scanned over its area in 1 mm steps while the transmission spectrum is recorded with the spectrograph. The spectrum was fit to find the birefringence using Equation 5, including the dispersion of the birefringence. The rms birefringence uniformity was calculated over a clear aperture equal to 80\% of the diameter of the crystal under test.

The quality of the crystals tested varied widely with the measured birefringence uniformity ranging between 2.2 and 112.1$ \cdot 10^{-6}$. Figure 3 shows examples of the birefringence uniformity of four crystals from four different vendors, on a common scale of $\pm 10^{-5}$. Both large scale variations and striations are evident. The variations are not due to figure errors. These are the best thick crystals from the four vendors. Two of these crystals meet the uniformity specification of Equation 8 including the $\sqrt{2}$ factor since they will be
used in a wide field configuration. Two thirds of all the crystals with thickness between 22 and 25 mm did not meet the birefringence uniformity requirement. A proportionally higher percentage of the thinner crystals did meet the requirement due to the easing of the requirement as 1/thickness. We conclude that crystals with the required birefringence uniformity can be obtained from commercial sources, but they will need to be carefully specified and selected.

4 EVALUATION OF LN ELECTRO-OPTIC TUNING

Many modern birefringent filters are tuned with nematic liquid crystals included in each filter stage. Direct electro-optic (EO) tuning of the LN crystals is desirable in that it would reduce the number of optical elements in the filter, and potentially allow faster tuning between wavelengths. Motivated by these improvements, we evaluated EO tuning of the LN crystals.

4.1 EXPERIMENTAL SETUP

Figure 4 (a) and (b) show the set-up used for the EO tuning measurements and a screenshot of the LabView interface, respectively. In order to test a large number of crystals without the added expense of having them all coated with transparent electrodes, we used glass plates coated with Indium Tin Oxide (ITO). We tested several y-cut LN crystals with different thicknesses. Figure 4 (a) shows two crystals of 25 mm thickness in the setup placed between the ITO coated glass plates used for applying voltage across the crystals. The crystal is also between two linear polarizers with polarization axis set at ±45˚ to the fast axis of the crystal. Light from a broadband source is collimated with a lens before the crystal and focused with another lens after the crystal onto an optical fiber which is fed into a spectrograph (Acton Spectrapro 2750). Selection of the wavelength region was carried out by rotating the grating. The transmission spectrum is recorded at the focal plane of the spectrograph with a CCD camera. The experiment is controlled with LabView. Figure 4 (b) shows a screenshot from one measurement, the top plot shows the image of the transmission channels recorded by the CCD and the mean transmission profile averaged along the slit is shown in the bottom plot. For applying voltage across the crystal, a zero-crossing high voltage dc power supply unit (Applied Kilovolts, HPZ series) which provides up to ±10 kV is used. The voltage output of the power supply is controlled by a proportional DC voltage of up to ±10 V which was generated with a National Instrument’s DAC board synchronized with the image acquisition.

4.2 LN EO TUNING

The birefringence of the LN can be altered by applying a voltage across the crystal. This can be used to vary the wavelength of the transmission peak when the crystal is used in a birefringent narrow-band filter. The change in birefringence depends on the direction of the applied voltage with respect to the crystal axes. In the present case the voltage is applied along the y-axis, which is also along the direction of propagation of the light. Equations describing the effective birefringence variation and the resulting wavelength shift are derived in the Appendix.
Figure 4 - (a) The experimental setup for measuring the EO tuning of LN crystals. The red and black wires are connected to the ITO coated glass plates and the LN crystal is placed between these plates. (b) A screenshot from one of the measurements. The top plot is an image from the CCD camera at the focal plane of the spectrograph showing the transmission spectrum and the bottom plot shows the corresponding spectrum averaged along the slit. The wavelength scales differ in the top and bottom plots.

Figure 5 - (a) The stacked transmission spectra for a single 25 mm LN crystal taken in the 616.5 nm wavelength region. Each spectrum corresponds to a different voltage with voltage varying between ±9 kV. (b) The average shift in transmission peak from four such measurements.

Figure 5 shows the results of one measurement of the shift in wavelength as a function of the applied voltage carried out on a single 25 mm thick y-cut LN crystal. Figure 5(a) shows the mean transmission profiles stacked vertically for different voltages centered around 616.5 nm. The applied voltage was varied from -9 kV to +9 kV, in 500 V steps. For each voltage, the transmission profile was recorded and later analyzed for the wavelength shift in the transmission peaks. The x-axis in the figure is in units of free spectral range (FSR), the wavelength separation between two transmission peaks, which in this case it is around 0.14 nm. In order to tune the filter electro-optically, one polarity of the voltage must be sufficient to shift the peak by at least half of the FSR. Figure 5 (b) shows the resulting shift in wavelength with the applied voltage. The solid red line is a linear fit to the mean of four measurements (filled circles). For the 25 mm LN crystal at 616.5 nm, the half-FSR was observed to be around ±7.8 kV. Similar measurements were repeated for several more crystals with the same thickness; we found small variations in the half-FSR voltage, which could be attributed to the slight variations in the electro-optics coefficients of the individual crystals.
In Figures 6 (a) and (b), we show similar measurements carried out on a 0.5 mm thick crystal at 525 nm. The mean wavelength shift is computed from two measurements. These are preliminary results for the thinner crystal as it was difficult to carry out the measurements with the ITO coated glass plates loosely placed on both sides of the crystal in close proximity. The half-FSR voltage (≈ ±5.5 kV) obtained for this crystal is slightly lower than that of the 25 mm crystal (≈ ±5.7 kV). These measurements will be repeated rigorously after coating the crystal surfaces with ITO at a later stage.

Figure 6 - (a) and (b) same as in Figure 5 (a) and (b), but for a crystal with thickness of 0.5 mm and at 525 nm wavelength. The applied voltage step is 200 volts.

4.3 WAVELENGTH DEPENDENCE OF THE HALF-WAVE VOLTAGE

For LN crystals, the FSR increases with wavelength. In order to quantify the wavelength dependence on the half-FSR voltage, we carried out similar measurements as described in section 4.2, with several 25 mm crystals at different wavelengths which spanned the wavelength range for the COSMO LC. In Figure 7 (a) we plot the result of one such measurement for all the wavelengths covered. The filled circles are the mean of four measurements and the solid lines are the fitted straight lines. As evident from the figure, the half-FSR voltage increases towards longer wavelengths. For example, at 525nm the half-FSR voltage of 5.75 kV should be compared with 18.4 kV at 1074 nm. Figure 7 (b) shows the calculated half-FSR voltage at different wavelengths which show a linear dependence with wavelength. Above 700 nm the half-FSR voltages exceed the power supply voltage limit of 10kV and the half-FSR voltages are extrapolated from the measurements of less than a complete ±half-FSR.
Figure 7 - (a) The wavelength shift measured in FSR units versus voltage at different wavelengths for a 25mm, LN y-cut crystal. (b) The calculated/extrapolated half-FSR voltages at different wavelengths.

4.4 TUNING THE WIDE-FIELD, SPLIT ELEMENT

The experiments described above were conducted on single crystals. As described in section 2, in order to achieve the widest FOV performance with minimal spectral shifts, we will construct the COSMO LC tunable filter with wide-field elements, as shown in Figure 2. In that case, the crystal elements are split into two halves of equal thickness and oriented with their axes crossed. A half wave plate is introduced between the split elements at 45 degrees. This configuration has an added advantage in terms of half-FSR voltage. By combining the split elements, the effective FSR of the units becomes half, whereas the voltage can be applied across the faces of both the crystals. This in effect reduces the half-FSR voltages measured above by a factor of 2.

Figure 8 - (a) The wavelength shift measured in FSR versus voltage at 616.5 nm for a wide field element comprised of two 25 mm thick elements. (b) The calculated/extrapolated half-FSR voltage at different wavelengths for single elements (upper filled circles) and measured half-FSR voltages for a split element at three different wavelengths (lower filled circles).

To demonstrate this, we constructed a wide field element comprised of two 25 mm thick elements and a half-wave plate, shown in Figure 4 (a), and measured the voltage response. The results from one measurement are given in Figure 8 which shows the half-FSR voltage reduced from ~8 kV to ~4 kV at 616.5 nm, as expected. For comparison we plot the half-FSR voltages obtained for a split element configuration.
and for a single 25 mm thick crystal in Figure 8 (b). The dashed lines and empty circles are values calculated from the single element measurements, whereas the three filled circles in the bottom are the measured voltages for the wide-field configuration at three different wavelengths. Then, high voltage supplies with a range of ±10 kV will be sufficient to tune the LC birefringent filter over its operating range from 530 to 1083 nm.

4.5 LN EO RESPONSE

A fast response of the filter is important as it needs to be tuned to different wavelength positions during observations. Especially in solar observations, scanning across a spectral line should be carried out quickly in order to reduce the effect of atmospheric seeing. We carried out a few tests on one of our 25 mm crystals, which could provide some insight on the response time of the EO effect. One limitation of this experiment was the response time of the high voltage power supply itself, which is quoted by the vendor at around 50ms.

For our tests we used square waves with different frequencies produced by the DAC board, which is then amplified by the high voltage power supply unit. The amplitude of the maximum and minimum input voltages were fixed at ±4.5 Volts, which produced a square wave of ±4.5 kV. This voltage swing was chosen to shift the transmission spectrum by a half-FSR at this wavelength. For this experiment, the CCD camera was replaced by a photomultiplier following the exit slit of the spectrograph. The spectrograph grating was rotated to place the minimum and maximum of the transmission spectrum at the exit slit at -4.5 kV and +4.5 kV, respectively.

Figure 9 (a) - (c) shows the response of the crystal to the applied square wave voltages at frequencies of 1, 5 and 10 Hz, respectively. The black line is the input applied by the DAQ to the power supply, the red is the response of the crystal measured from the output of the photomultiplier detector and the green line shows the measured output from the high voltage power supply sampled by a high voltage probe.

Figure 9 - (a) – (c) Plots for the response time of the EO effect in LN crystals. The intensity is measured using a photomultiplier tube, tuned to the transmission channel peak at the exit slit of the spectrograph.

As the plots show, the response time of the crystal is approximately as fast as the response time of the high voltage power supply unit. In order to measure the exact response time a high voltage power supply unit with a very shorter settling time is required. The effective capacitance will increase in the case of thinner crystals, which may slow the EO response to the applied voltage. Characterizing the response time for the thinner crystal will be carried out at later stage.
5 CONCLUSION

Synoptic monitoring of coronal magnetism is important to our future understanding and prediction of space weather events which can damage critical infrastructures. The COSMO Large Coronagraph is a telescope specifically designed to measure the strength and direction of coronal magnetism over a 1° FOV with a 1.5 m aperture. This combination results in an étendue of $1.39 \, \text{m}^2\text{deg}^2$ which needs to be accommodated by post-focus instrumentation that must achieve a spectral resolution greater than 8000 over the wavelength range of 530 to 1083 nm.

This challenging set of requirements can be met with a tunable wide-field birefringent filter based on LN crystals. LN crystals with adequate birefringence uniformity are commercially available, and they offer the possibility of rapid electro optical tuning. LN offers an excellent alternative to traditional calcite crystals; it is available in much larger diameters and while its birefringence is only a factor of two less than calcite, the angular sensitivity of its wavelength shift is a factor of 10 less than that of calcite.

The engineering behind the COSMO LC is now mature. The optical design is well developed (see COSMOLC-DE-2003 Optical Design Description Document). The dome and telescope structure are modest by astronomical standards. The 1.5-m refractive primary is challenging and would make the LC the largest refracting telescope in the world. However, technological capabilities have advanced greatly since the completion of the Yerkes 1m telescope in 1896 and a 1.5-m refractive objective is now feasible with current technological capabilities (Nelson et al., 2008). Overall, we believe that construction of the COSMO LC presents low risk.

In closing, while the COSMO LC has an étendue which is two orders of magnitude below that of the LSST, given the LSST spectral resolution of ~6 (Olivier et al., 2008), the COSMO LC weighs in with an étendue resolution product about 5 times larger than the LSST!
6 REFERENCES


Evans, J. W., 1949, JOSA, 39, 229.


Title, A., 1974, Solar Phys, 39, 505.

Title, A. and Rosenberg, 1979, Applied Optics, 18, No. 20, 3443.


7 APPENDIX: CHANGE IN BIREFRINGENCE OF LN BY THE APPLICATION OF AN ELECTRIC FIELD

[Several equations were skipped; in case it is required we can add those]

In the presence of electric-field, in general, the index ellipsoid for LN can be written as,

\[
x^2 \left[ \frac{1}{n_o^2} - r_{22} E_y + r_{33} E_z \right] + y^2 \left[ \frac{1}{n_o^2} + r_{22} E_y + r_{33} E_z \right] + z^2 \left[ \frac{1}{n_e^2} + r_{33} E_z \right] + 2 y z [r_{51} E_y] = 0
\]

In our configuration for the birefringent filter, the applied electric-field is along the y-axis, the light propagation is also along the y-axis,

\[ E_y = E, E_x = 0, E_z = 0; \]

\[
x^2 \left[ \frac{1}{n_o^2} - r_{22} E_y \right] + y^2 \left[ \frac{1}{n_o^2} + r_{22} E_y \right] + z^2 \left[ \frac{1}{n_e^2} + r_{33} E_z \right] + 2 y z [r_{51} E_y] = 1 \tag{1}
\]

In the presence of an external electric field, the index ellipsoid of the crystal no longer can be described by the principal index ellipsoid equation due to the presence of mixed product terms. This is an indication of the change of orientation of the index ellipsoid. In the above case the only cross term present is yz, indicating a rotation in the y and z keeping the x-axis intact. In order to make the cross term vanishing, the axis transformation can take the following form,

\[ x = x' \]
\[ y = y' \cos \theta - z' \sin \theta \]
\[ z = y' \sin \theta + z' \cos \theta \]

Substituting these in eqn. 1 and solving for theta by making the cross term vanishing,

\[
\theta = \frac{1}{2} \tan^{-1} \left[ \frac{2 E_y r_{51}}{\frac{1}{n_o^2} - \frac{1}{n_e^2} + r_{22} E_y} \right]
\]

Then new indices along the x’, y’ and z’ can be written as;

\[
\frac{1}{n_{x'}^2} = \frac{1}{n_o^2} - r_{22} E_y
\]
\[
\frac{1}{n_{y'}^2} = \cos^2 \theta \left[ \frac{1}{n_o^2} \right] + \sin^2 \theta \left[ \frac{1}{n_e^2} \right] + r_{22} E_y \cos^2 \theta + 2 E_y r_{51} \sin \theta \cos \theta
\]
\[
\frac{1}{n_{z'}^2} = \sin^2 \theta \left[ \frac{1}{n_o^2} \right] + \cos^2 \theta \left[ \frac{1}{n_e^2} \right] + r_{22} E_y \sin^2 \theta - 2 E_y r_{51} \sin \theta \cos \theta
\]

In our case since the light propagation is along the y-axis, the indices along the x and z will participate in the effective birefringence change, i.e., the above equations can be simplified to obtain,

\[
n_{e'} = n_o + \frac{1}{2} n_o^3 r_{22} E_y
\]
\[
n_{e'} = n_e - \frac{1}{2} n_e^3 \sin \theta \left[ \frac{1}{n_o^2} - \frac{1}{n_e^2} + r_{22} E_y \right] \sin \theta - 2 E_y r_{51} \cos \theta
\]

This gives the change in birefringence as;
\[ \Delta J \approx (n_e - n_o) - \frac{1}{2} n_o^3 r_{22} E_y - \frac{1}{2} n_e^3 \sin \theta \left( \frac{1}{n_o^2} - \frac{1}{n_e^2} + r_{22} E_y \right) \sin \theta - 2 E_y r_{51} \cos \theta \]

This will introduce a wavelength shift of:

\[ \Delta \lambda = \lambda_0 \left( \frac{J_1}{J_0} - 1 \right) \]

where \( J_0 \) is the birefringence before applying the voltage, i.e.

\[ J_0 = n_e - n_o, \quad J_1 = J_0 + \Delta J \]

While calculating the wavelength shift of the birefringence, the effective refractive index should be taken into account as described in Title, 1974, Solar Physics, 39, 505.