Application of LC and LCoS in Multispectral Polarized Scene Projector (MPSP)

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ABSTRACT

A Multispectral Polarized Scene Projector (MPSP) had been developed in the short-wave infrared (SWIR) regime for the test & evaluation (T&E) of spectro-polarimetric imaging sensors. This MPSP generates multispectral and hyperspectral video images (up to 200 Hz) with 512×512 spatial resolution with active spatial, spectral, and polarization modulation with controlled bandwidth. It projects input SWIR radiant intensity scenes from stored memory with user selectable wavelength and bandwidth, as well as polarization states (six different states) controllable on a pixel level. The spectral contents are implemented by a tunable filter with variable bandpass built based on liquid crystal (LC) material, together with one passive visible and one passive SWIR cholesteric liquid crystal (CLC) notch filters, and one switchable CLC notch filter. The core of the MPSP hardware is the liquid-crystal-on-silicon (LCoS) spatial light modulators (SLMs) for intensity control and polarization modulation.

Keywords: Liquid crystal (LC), Spectral filter, Notch filter, Liquid crystal-on-silicon (LCoS), polarization mapping, cholesteric liquid crystal (CLC), switchable filter, spatial light modulator, spectro-polarimetric

1. INTRODUCTION

The polarization information has got more attentions in recent years and been used to improve detection, identification, and recognition of manmade objects and other obscured targets of strategic interest in highly cluttered backgrounds, as another more powerful tool apart from the multispectral image detection that using conventional intensity and wavelength imaging techniques. This is so-called polarimetric imaging/monitoring[1,2], which has proved to be a powerful tool in detecting such objects by significantly enhancing the contrast of materials in an image due to surface features, shape, shading, and roughness, particularly when there is little contrast in the intensity and wavelength imagery. Specifically, manmade objects exhibit general polarization features due to the composition of their surfaces, i.e., being metal or plastic. Combining the spectral characteristics that is based on the multispectral image detection techniques with the polarization features has led to the development of spectro-polarimetric imaging sensors, which are an enhanced version of the multispectral sensor with a polarization mode capability. Various SWIR, MWIR, and LWIR polarimetric imaging systems[3,4] have been developed. Such polarimetry imaging, being a special case of general polarimetry, can be used to map the state of polarization of each pixel in a scene.

In order to validate these newly developed spectral polarimetric imaging sensors, via test and evaluation (T&E) in a laboratory environment, which is extremely important to enable accurate calibration at a reduced cost, *Kent Optronics, Inc*. (KOI) has developed a multispectral polarized scene projector (MPSP) system under U.S. Army support. This MPSP system enables spatial, spectral, and active polarization modulation, and generates a known wavelength, controlled bandwidth, and mapped projected polarization image or motion picture display. The MPSP's capabilities make it a suitable T&E tool for characterization of spectro-polarimetric sensors and it could aid in the future development of spectro-polarimetric imagers with specified characteristics. Such a fully integrated MPSP system which passed critical design reviews and system compliance tests has been described previously[5]. This system has been delivered to the U.S. Army Research Laboratory (ARL), Adelphi, MD and installed there. The MPSP is a standalone turnkey instrument that can project stored images and/or motion pictures directly onto the entrance of a spectro-polarimetric sensor or unit under test (UUT). Users can input parameters such as picture brightness (radiance), wavelength, bandwidth, and polarization states at the individual pixel level to simulate the displayed targets and scenes.

Of the MPSP system, the core subsystems are the liquid crystal (LC) material based variable bandwidth spectral tunable filter assembly, and the liquid crystal-on-silicon (LCoS) based spatial light modulators (SLMs) for intensity control and polarization modulation.

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2. VARIABLE BANDWIDTH SPECTRAL TUNABLE FILTER ASSEMBLY

As mentioned earlier, one of the core subsystems in the MPSP equipment is the liquid crystal (LC) material based variable bandwidth spectral tunable filter assembly. The basic function of the variable bandwidth tunable filter is to tailor the very broadband light source to the desired operating wavelength range of 850–1650 nm in the short-wave infrared (SWIR) band with a desired bandwidth (12–100 nm). This allows users to independently select the desired wavelength (λ) and bandwidth (Δλ) to match the spectro-polarimetric sensor under test. The spectral bandwidth has a discrete value between 12 and 100 nm within the wavelength range 850 to 1650 nm.

The assembly consists of two passive cholesteric liquid crystal (CLC) based broadband Notch filter: one is in the visible region of 450–750 nm; another is in the SWIR region of 1800–3000 nm, with one more active (switchable) CLC broadband Notch filter in the near infrared (NIR) region of 750–1250 nm, and the key LC spectral tunable filter with modified Lyot configuration. The schematic diagram of the filter assembly is shown in Figure 1. The optical head size of the filter is around 6"(L)×4"(W)×3.5"(H) and it has a clear aperture of 1"×1".

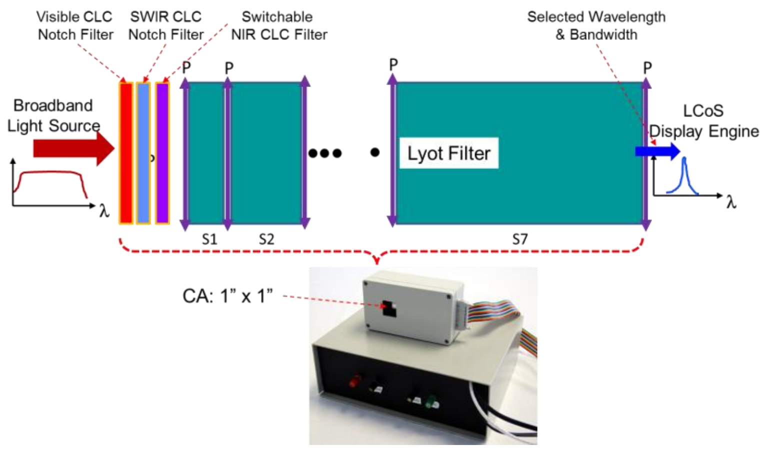

Figure 1. Configuration of the LC material based variable bandwidth spectral tunable filter assembly

2.1 Broadband CLC Notch filter

The cholesteric liquid crystal (CLC) Notch filter consists of two films: one is the right-handed (RH) CLC and another is the left-handed (LH) CLC film. A conventional CLC film has a constant pitch that yields a narrow band selective reflection (Notch) at the wavelength given by $\lambda = n_a \bullet P$, where n_a is the average CLC refractive index and P is the CLC pitch. Its bandwidth is given by $\Delta\lambda = \Delta n \bullet P$, where Δn is the CLC birefringence. Conventional CLC has a $\Delta\lambda$ around 40 to 60 nm in visible. Generally, a right-handed (RH) CLC film reflects the wavelength band that matches its pitch and bandwidth in the similar RH handedness; while transmits the rest in the opposite LH handedness. For a beam of the non-polarized (natural) light, one handedness CLC film only reflects the 50% of the incident beam and transmits 50% due to that the non-polarized light could be taken as intensity superposition of 50% RH and 50% LH beam. Therefore, a CLC Notch filter is a stack of one RH CLC and one LH CLC films.

KOI's broadband CLC Notch filter is based on the novel polymer stabilized cholesteric liquid crystal technology with a limited pitch-gradient instead of the constant pitch. The pitch gradient is created via the UV Polymerization Induced Molecular Redistribution mechanism. It has been discovered that the pitch gradient is governed by UV curing light intensity, CLC thickness, and liquid crystal (LC) material composition that is further related to LC chemical structure. By adjusting the curing condition as well as the material composition, different bandwidth broadband CLCs have been obtained with any bandwidth between 60 nm and over 1000 nm in spectral region from visible to SWIR.

2.2 Passive broadband CLC Notch filter in visible and SWIR

The passive broadband CLC film is made from a liquid crystal mixture containing polymerable liquid crystalline compound, non-polymeric LC compounds, chiral additives (RH and LH respectively), photo-initiator, and sometimes a bit of inhibitor. The inhibitor can prolong the polymerization rate to let LC molecules have sufficient time to phase separate, diffuse, and re-distribution. The mixture is weighed per the pre-determined ratio and mechanically mixed.

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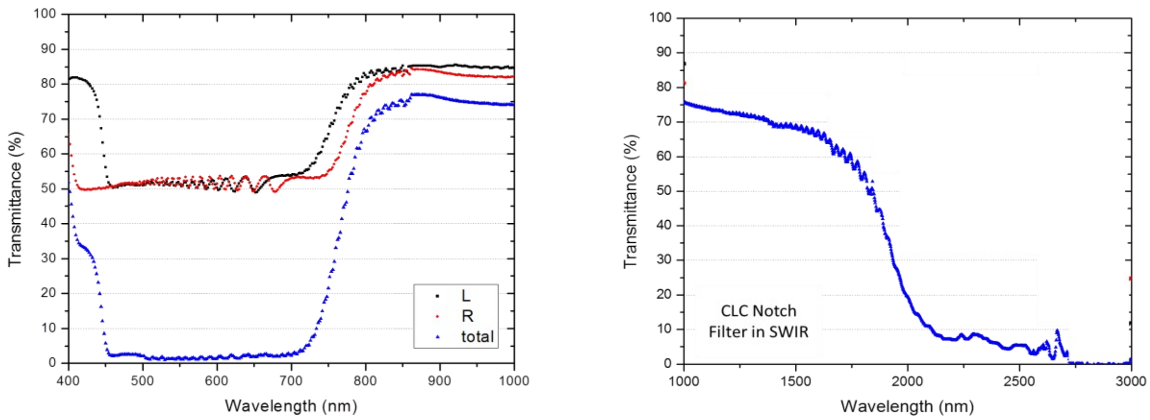
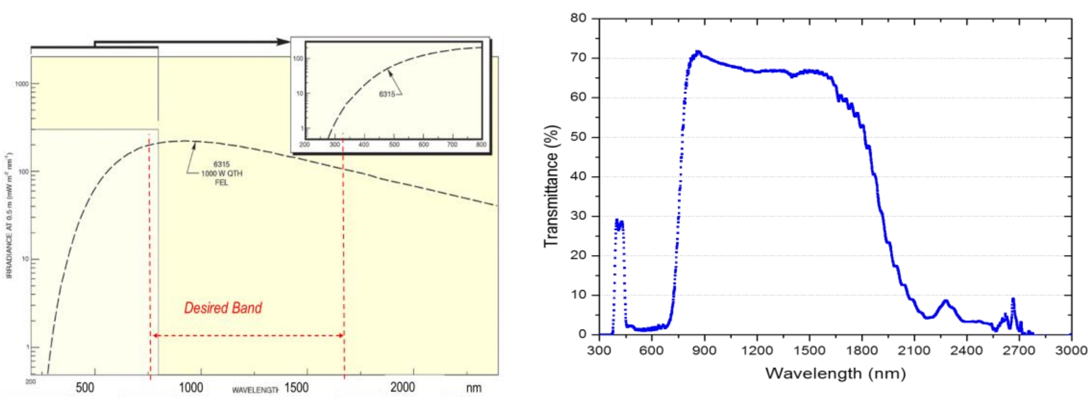
Empty liquid crystal cell is prepared using glass substrates. The glass is ultra-sonically bathed followed by coating, baking, and rubbing polyimide alignment layer. Finally, two pieces of processed glass substrates are assembled to form an empty cell. Next, the LC mixture is vacuum filled into the empty cell followed by a thermal annealing for a certain period. Finally, the LC sample is cured with UV having a suitable intensity for creating a CLC pitch gradient. Figure 2a illustrates the spectral characteristics of the RH, LH and CLC paired Notch filter in visible, its notch band is from 450 nm to 750 nm. Figure 2b displays the spectral feature of the CLC paired filter in SWIR, its notch band is from 1800 nm to 3000 nm. No anti-reflection (AR) coatings were applied to the substrate glass surfaces. Therefore, the out-band transmittance maximum is around 75%.



(a) (b)

Figure 2. Passive broadband CLC Notch filters in (a) visible and (b) SWIR regions

As can be seen from Figure 2a, both RH and LH CLC films have nice spectral feature with sharp reflection band edges. Although the LH CLC reflection band is slightly narrower than that of RH CLC, their pair shows good contrast ratio of around 50:1 in the reflection band, which well services the purpose as pre-filtering in the tunable filter assembly. The CLC film thickness (cell gap) is 15 μm. Usually glycerin index-matching fluid is applied between the CLC paired films to reduce Fresnel loss, which contribute high contrast ratio as well. The paired CLC filter in SWIR in Figure 2b has relatively lower contrast ratio of around 10:1, largely due to the limited cell gap of 25 μm, and no good index-matching fluid for such broad region. The sharp drop starting from 2750 nm is due to ITO and glass substrate absorption. Nevertheless, it serves well for the pre-filtering in the tunable filter assembly again.



(a) (b)

Figure 3. Spectra from (a) tungsten halogen light source, and (b) combination of the visible and SWIR CLC filters

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The long-term stability of the broadband CLC filters have been examined. After more than six months of fabrication, the transmission spectra of the set of CLC pair has neither considerable degradation nor change, indicating a good stability and reliability, thanks to the high density of cross-link polymer networks. This is the major difference between the conventional CLC and the passive broadband CLC where the former has almost no polymer networks. The difference between the visible and the SWIR CLC is the difference in the content of the chiral dopants. There are high content chiral dopants in the CLC mixture for visible.

Figure 3a illustrates the light source spectrum from 1000 W Oriel Quartz Tungsten Halogen, where the band between two red dash lines indicates the desired operating wavelength range; Figure 3b displays the transmission from the combination of the two-passive broadband CLC filters mentioned above. The slight leakage around 450 nm, which was from the visible CLC as shown in figure 2a will not affect the performance of the entire filter assembly at all.

2.3 Variable bandwidth tunable filter

The KOI's variable bandwidth spectral tunable filter in the MPSP system is based on the modified Lyot filter[6] with liquid crystal phase retarder as each stage. A Lyot filter is a type of optical filter that uses birefringence material sandwiched in two polarizers to produce a narrow bandpass of transmitted wavelengths. It is made of a series of stages (birefringent plate) with the thickness doubled compared to the previous one. Generally, the thickest stage sets the bandwidth and the thinnest stage sets the Free Spectral Range. The transmission, *T*, of an *N*-staged Lyot filter is

$$T = (\cos\frac{\Gamma_1}{2}\cdot\cos\frac{\Gamma_2}{2}\cdots\cos\frac{\Gamma_N}{2})^2 = \frac{\sin^2(2^N\cdot\frac{\Gamma_1}{2})}{2^{2N}\cdot\sin^2(\frac{\Gamma_1}{2})} \tag{1}$$

where Γ is the phase retardation ($\Gamma = \frac{2\pi\Delta nd}{\lambda}$), Δn is the LC birefringence and *d* is the thinnest cell thickness with $\Gamma_2 = 2\bullet\Gamma_1$, $\Gamma_3 = 2\bullet\Gamma_2$,……. Its central wavelength, $\lambda_{central}$, and bandwidth as full width at half maximum, FWHM, are

$$\lambda_{central} = \frac{\Delta n\cdot d}{m} \quad \text{and} \quad FWHM = \frac{\lambda_{central}}{2^N\cdot m} \tag{2}$$

The Free Spectral Range (FSR) or the tuning dynamic range is:

$$FSR = \frac{\lambda_{peak}}{m+1} \tag{3}$$

where *m* is the order number, m=1, 2, 3…. By varying the phase retardation of each stage correspondingly with LC molecules tilted under the applied e-field, the central wavelength can be tuned electrically within the range of FSR.

In order to achieve the desired operating wavelength range of 850–1650 nm with FSR of 800 nm, and the variable bandwidth from 12 to 100 nm, total 7-staged Lyot filter at 1st order was designed. In the design, the reduction of the light leakage (side lobes) near the bandpass has been considered. The simulation shows that the leaked side-lobe transmission is only around 1.1% with the narrowest bandwidth of 10.89 nm at 850 nm. The schematic diagram of the modified Lyot filter configuration is illustrated in figure 1.

Although the pre-filters cut the all light wavelengths out of the operating range, the Lyot filter still would be transparent for a half wavelength in the higher order. For example, when the tunable filter opens at 1600 nm wavelength, the double frequency or half wavelength of 800 nm will pass too. In order to block the double frequency wavelength beam pass, a switchable CLC filter was introduced, which would cut off any wavelengths shorter than 1000 nm. That means when tunable filter operates in the range of 1250 – 1650 nm, the switchable CLC filter is at blocking states; when tunable filter operates in the range of 850 – 1250 nm, the switchable CLC filter is at transmissive states.

2.4 Active (switchable) broadband CLC Notch filter in NIR

The active (switchable) broadband CLC Notch filter is similar to the passive one in the material mixture content. The major difference is that the switchable CLC has lower density of cross-link networks with flexibility than that in the passive ones, which allows the LC molecules to be reoriented along the electrical field when an e-field is applied. Once

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the e-field is off, the LC molecules will realign to their originally aligned orientations by the polymer networks. For the operating wavelength 850 – 1650 nm region, glass substrate with ITO coatings is a good choice, which enable to apply the e-field across the cell. Generally, an e-field of around 10–20 V/um is sufficient to make the CLC molecules un-twisted to be homeotropic, which is completely transparent for any wavelength. Figure 4 shows the transmittance spectrum of the active broadband CLC filter in NIR range with on- and off-state, where a voltage of 280 volts was applied to make the NIR CLC filter be transparent. The transmittance is around 80%. No AR coatings were applied to the substrate glass.

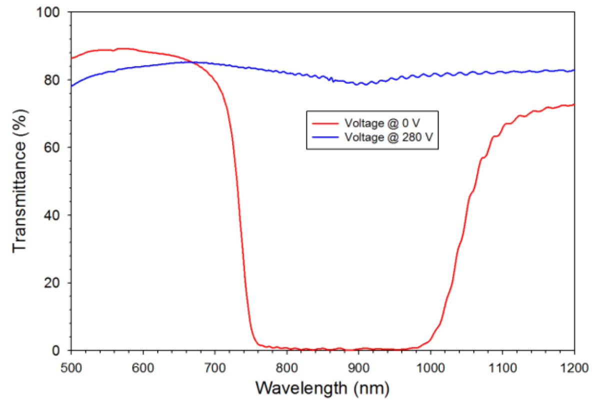
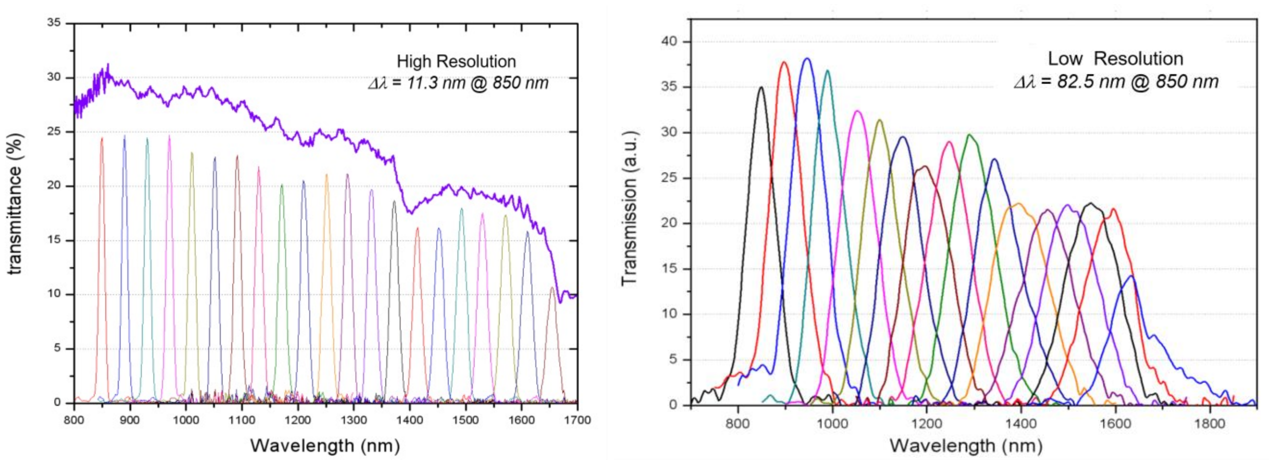


Figure 4. Transmissive spectrum from a switchable CLC filter in NIR

2.5 Variable bandwidth spectral tunable filter assembly

As shown in Figure 1, the variable bandwidth spectral tunable filter assembly consists of three broadband CLC filters and one modified Lyot filter. Figure 5 illustrates the two examples: one is tuning with narrowest (high resolution) bandwidth for hyperspectral imaging and another is broadest (low resolution) bandwidth for multispectral imaging for the MPSP system. Different combinations can generate a different discrete bandwidth between these broadest and narrowest range. As can be seen, the maximum transmittance for the high resolution is around 24% while for low resolution is around 37%, respectively. The minimum transmittance for the high resolution is around 15% while for low resolution is around 22%, respectively, except ones around 1650 nm where the ITO absorption takes places, which is around 10% and 14% respectively due to the ITO absorption. The ITO absorption also occurs at around 1400 nm. The transmission curve on the top of the tuning peaks in the high-resolution spectra graph is the transmittance of the entire assembly in the transmissive state when all stages are in clear states with the voltage on.



(a) (b)

Figure 5. Typical spectral profile from variable bandwidth tunable filter assembly (a) high and (b) low resolutions

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3. LCOS SPATIAL LIGHT MODULATOR (SLM)

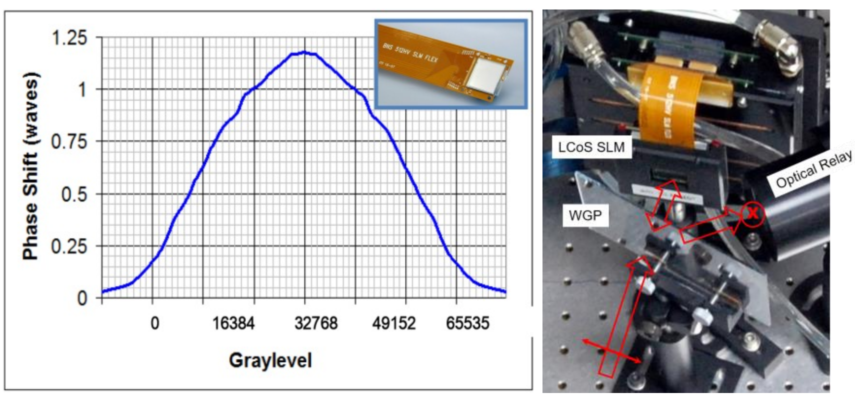
Another core technology in the MPSP system mentioned earlier is the liquid crystal-on-silicon (LCoS) based spatial light modulators (SLMs) for intensity control and polarization modulation.

3.1 LCoS SLM display engine

The liquid-crystal-on-silicon (LCoS) spatial light modulator (SLM) is made by *Boulder Nonlinear Systems*, *Inc*. The SLM has 512×512 pixels with the pitch size of 37.5 μm. The cover glass of the SLM was coated with a broadband AR coating between 850 and 1650 nm to minimize the Fresnel reflection. The thin cell gap of the LCoS SLMs and high figure-of-merit (FoM) LC material lead to the fast response up to 350 Hz frame rate. The liquid crystal layer is sandwiched between backplane with pixel array and a cover glass. The cover glass is coated with a transparent conductive oxide layer that serves as a common electrode. Circuitry within the backplane provides an individually programmable analog voltage at each pixel. When different voltages are applied to the pixel array a varying electric field is produced across the liquid crystal layer, rotating the liquid crystal molecules above each pixel. The backplane pixels are aluminum and therefore serve as both electrodes and mirrors in a reflective configuration. Voltages on the pixels can be programmed to 65535 different values ranging between 0 and V_{max} - a device dependent value, which is 18V in the MPSP system. Generally, a pair of crossed polarizers is used with LCoS SLM for the intensity display.

A typical optical response curve is shown in Figure 6a, where inset is the LCoS device optical head. When a full voltage is applied (pixel value 0) the phase retardation of the LC is minimum. When no field is applied (pixel value 32768) the phase retardation by the liquid crystal is maximum. The is because the LC is aligned homogeneously. Thus, the valid grayscale values are 0 – 32767, which is programed to be proportional to the phase retardation.

There is a 45° alignment angle between the LCoS optic axis and the polarization axis of the linearly polarized light coming from the tunable filter assembly. Characterizations were carried out on the display engine to measure the electro-optical (EO) response time. The measurements indicate that a maximum frame rate of 350-Hz was achieved, responsible from the relatively thin cell gap of the LCoS and the high figure-of-merit (FoM) LC material. The dynamic range of the display image brightness was also measured to be 14 bits, driven by the 16-bit PCIe (Peripheral Component Interconnect Express) driver. The loss of the 2-bit dynamic range is attributed to the initial contrast ratio and the intensity non-uniformity of the display engine. Figure 6b illustrates the experimental setup for the LCoS intensity display engine.



(a) (b)

Figure 6. (a) Typical optical response from LCoS device and (b) setup of LCoS display engine

3.2 Phase SLM units and polarization coding

In the display engine, the LCoS modulates the incident light beam through the phase retardation; the degree of the retardation is reflected by intensity (brightness) through a polarization analyzer. The intensity contrast indicates the magnitude of the phase retardation at pixel level. Similarly, in the phase mapping the LCoS introduces the phase retardation but without involving any polarization analyzer. There is no intensity change “seen” by a non-polarimetric sensor even the phase has been modulated. As can be seen, the major difference between the LCoS display engine and the phase coding is if there is a polarization analyzer after LCoS SLM.

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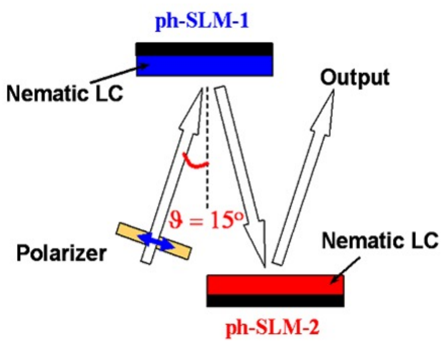
The goal of the polarization mapping in MPSP system is to encode the six polarization states: linear horizontal polarization (LHP), linear vertical polarization (LVP), linear +45 ° (L45P), linear -45 ° (L45M), right-handed circular polarization (RCP), and left-handed circular polarization (LCP) in pixel level within the operation wavelength range of 850–1650 nm. The polarization coding is implemented using two phase SLM units. In order to code the correct phase of the objects, the grayscale versus phase retardation relationship must be pre-characterized. All the desired phase retardations can be achieved by electrically tuning LC material inside the phase SLM devices. The required Δn to achieve the same phase retardation at different wavelength is different, based on the phase retardation equation as shown below.

$$\Phi = \frac{2\pi \Delta n d}{\lambda} \tag{4}$$

where Φ is the phase retardation, Δn is birefringence, d is the optical path (two times of the cell gap under the reflective mode), and λ is the wavelength. In practice adjusting the voltages applied on each pixel can adjust the birefringence of that pixel to achieve desired phase retardation for a certain wavelength. Such voltage adjustment can be easily implemented in the LCoS SLM software with a calibrated look-up-table (LUT). No hardware modification is required.

At the wavelength selected by the tunable filter, these phase SLMs provide 0 to 1.5π phase retardance with an optic axis orientation of 45° and 0 to π phase retardance with an optic axis orientation of 22.5° with respect to the light's polarization as projected from the display engine. Figure 7a illustrates the schematic diagram of the two phase LCoS SLM configuration, and Figure 7b is the phase retardation required for each phase LCoS SLM to achieve the six polarization states together to form the Stokes parameter. In principle, not only one of the six polarization states – LHP, LVP, L45P, L45M, RCP, and LCP – but also any elliptical polarization states can be generated at each individual pixel level, if grayscale versus phase retardation relationship are properly pre-calibrated. For example, if both phase SLM set to 0-phase retardance, the output polarization would be no change, same as the incoming polarization from the display SLM, in this case is the LHP.



Output	LHP	LVP	L45P	L45M	RCP	LCP
Ph-SLM-1	Φ=0	Φ=π	Φ=0	Φ= π	Φ=3/2 π	Φ=1/2 π
Ph-SLM-2	Φ=0	Φ=0	Φ= π	Φ= π	Φ=0	Φ=0

(a) (b)

Figure 7. (a) Schematic diagram of phase SLM configuration and (b) required retardance for six polarization states

3.3 Polarimetric sensor and Stokes parameter

Stokes parameter images of S_1 = LHP – LVP, S_2 = L45P – L45M, and S_3 = RCP –LCP can be obtained through processing the images recorded by polarimetric sensor with the sensor analyzers matching to LHP, LVP, L45P, L45M, RCP and LCP, respectively. The images of $DOLP = \sqrt{S_1^2 + S_2^2} / S_0$ and ($DOCP = S_3 / S_0$), which are the degree of linear polarization and the degree of circular polarization respectively can also be processed[5], as illustrated in Figure 8a and 8b respectively. For comparison, Figure 8c shows the intensity image recorded by a non-polarimetric camera. As can be seen, the interesting objects, particularly the road to tower, originally were buried or covered in the intensity image recorded by conventional (non-polarimetric) sensor, now can show up being clearly "visible", thus some objects with distinct polarization features can be identified. Such analysis of the combination of the Stokes parameters and the DOLP and DOCP indicate that the polarimetric imaging and detection can be very powerful tools in the military operations. They would allow users to discriminate between natural and manmade objects, which are usually either linearly polarized or partially polarized due to their metal /plastic surfaces.

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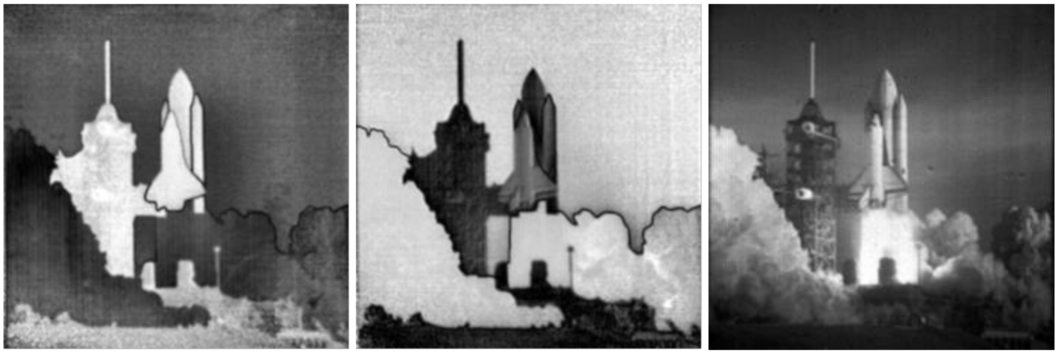

(a) (b) (c)

Figure 8. Processed images of (a) DOLP, (b) DOCP, and (c) intensity only

4. CONCLUSION

The variable bandwidth spectral tunable filter assembly has been designed, fabricated; performance tested and passed the system compliance tests. The first two passive broadband CLC filers in the filter assembly are used to tailor the very broadband tungsten halogen light source. The modified Lyot filter is capable to generate the operating wavelength range of 850–1650 nm, where the bandwidth can be selected with discrete value in the bandwidth range of 12–100 nm. This allows users to independently select the desired wavelength (λ) and bandwidth ($\Delta\lambda$) to match the spectro-polarimetric sensor under test. One LCoS SLM has used to individually modulate the intensity of the illuminating light beam to embed the intensity information, thereby generating the pixilated intensity image frames based on the input digital images. Cascades of two LCoS SLMs have been used to map the phase retardance and thus the polarization state at each pixel, which encodes the scene (image) with six polarization states. Therefore, the MPSP system can project the image with defined wavelength, bandwidth, and desired polarization states, which is desired tool for a complete T&E of the spectro-polarimetric sensors or UUTs.

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