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Multi-spectral Tunable Detection (MultiTuDe) Lens for Rapid In-situ Forensic Analysis

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Abstract

Contrast enhancement techniques that use forensic light sources (FLS) with spectral bandpass filters, are widely used by the forensic community. Biological fluids, prints, trace material detection, and document analysis are some of the common targets and applications. Most current instruments and procedures are manual, labor intensive, generally require a darkened environment, and pose significant logistical challenges for field application.

The goal of Teledyne Scientific and Imaging (TS&I) is to enable an integrated multispectral imaging triage/survey tool capable of nearly real time enhancement of target signatures of forensic interest by collecting and analyzing different wavelength and polarization channels using passive or active illumination (e.g. multi-wavelength LED flash), and using powerful backend processing algorithms. Our previous work demonstrated feasibility of the concept through brass-board camera implementation and off-line image processing. We optimized a traditional birefringent filter design (Lyot filter) via novel materials and engineering, for enhanced transmission (particularly at shorter wavelength) and fast speed. We used this electro-optically (EO) tunable bandpass filter along with a specially designed commercial off-the-shelf multispectral lens (optimized over broad wavelength range eliminating need to refocus as the wavelength changes) along with a monochrome camera as the imaging hardware. While we demonstrated a fast EO tuned multispectral imaging system, the complexity (e.g. number of components, temperature sensitivity and stabilization, dual frequency electronic drive) and the cost of both filter and lens proved to be a big impediment to potential transition to an affordable product.

This project was motivated by the desire to enable an inherently low-cost multispectral imaging system, while retaining the advantages of the traditional liquid crystal tunable filter (LCTF) hardware. We developed a highly unconventional and innovative reflective lens design that uses a tunable cholesteric liquid crystal (ChLC) cell as a narrowband EO tuned reflector, the critical spectral control element. The design embodies the following novel characteristics:

- Use of a single ChLC cell, a natural band-rejection filter, to replace the optical stack of five nematic LC cells in a traditional birefringent filter design.
- Use of a single linear polarizer with a broadband quarter-wave plate instead of six polarizers in a traditional birefringent filter design.
- A unique optical design to convert the spectral filtering from a rejection band to a passing band, providing broad spectral tuning range, adequate Field of View (FOV), optimal imaging resolution and contrast, and finally,
- A nominally linear DC voltage dependence of the center wavelength of the narrow passband that enables a simple addressing scheme, and the elimination of temperature stabilization of complex dual frequency addressed LC cells (used in the past work).

We met all the primary goals of this project. We demonstrated tunable ChLC cells that work over nominally 400-800 nm wavelength range with high contrast. We developed the lens optical design using Zemax raytrace simulation to maximize the FOV, with spot size and image MTF (modulation transfer function) consistent with the selected camera. We developed an optomechanical package around the optical prescription. We fabricated custom lenses, mirrors, and polarization elements and aligned and assembled them into modular sub-assemblies. Finally, we integrated, tested and demonstrated the Multi-spectral Tunable Detection (MultiTuDe) Lens.

This report describes in detail, the tunable ChLC cell background, fabrication and testing, lens design considerations, optical assembly and integration approach, test results, application and transition considerations, and the next steps.

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Executive Summary

The forensic community employs numerous contrast enhancement techniques that use forensic light sources (FLS) with multiple wavelength filters, off-axis illumination for prints, and fluorescence imaging for bio-fluids. Given the laborious and time-consuming nature of forensic imaging, post-processing and visualization along with logistical challenges such as need for darkening the environment, there is need for a rapid triage/survey camera that will enable a practitioner to effectively visualize, prioritize, and guide data collection and processing beyond what current tools can do. There is a need for a tool that can rapidly survey a crime scene and provide nearly real time (~1 second processing time, not video rate) information to help plan and prioritize the investigation. Our past work demonstrated feasibility of the concept through brass-board camera implementation and off-line image processing [1,2].

Current work is motivated by the desire to significantly reduce the cost and complexity of an imaging system capable of electro-optically tuned non-mechanical multispectral analysis. In the process, we developed, implemented and demonstrated a unique lens design to achieve that goal. See Figure 1.

Figure 1 Integrated MultiTuDe lens mounted on a COTS monochrome camera

There are two key technology advances at the heart of this demonstration: (1) a continuously electrically tunable ChLC filter that achieves narrow spectral band reflection with a single liquid crystal (LC) cell and a single polarizer with a simple addressing scheme that does not require temperature stabilization or complex calibration; and (2) a novel lens design that allows the tunable ChLC filter to be used as an integral part of a reflective lens design to form the MultiTuDe Lens. The lens design essentially converts this tunable reflective band-block element to a tunable band-pass imaging device. The filter and lens are truly integrated in this lens design. The lens works with polarized light and a broadband circular polarizer covering the functional bandwidth (visible-NIR) is used in front of the lens. Figure 2 illustrates the basic concept. The simplicity of the design enables an order of magnitude reduction in bill of material cost over a birefringent filter based approach.

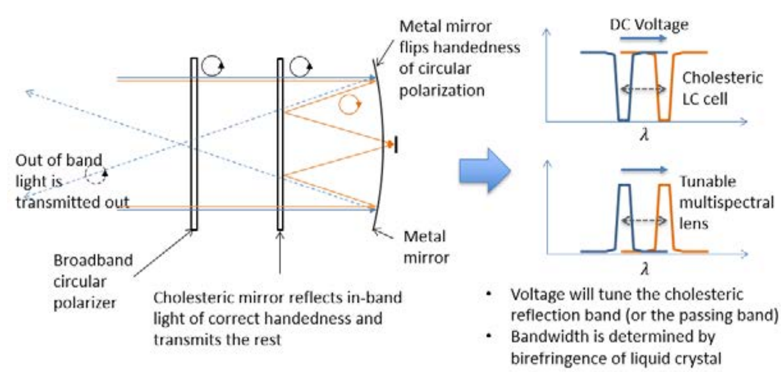


Figure 2 Conceptual design of MultiTuDe tunable multispectral lens

The primary challenges for the project were formulation of high contrast liquid crystal tunable filters that will function over sufficiently large free spectral range and achieving high quality imaging over sufficiently wide FOV with a reflective (catadioptric) lens design. We overcame the first challenge through extensive material and device optimization. We addressed the second challenge with the optical design optimization starting with the simple conceptual design (Figure 2) to maximize performance is terms of image quality, field of view, stray light performance etc. We were able to demonstrate a prototype with compelling performance. We used custom refractive lenses and a custom aspheric primary mirror to enhance the field of view. The operational or the free spectral range of the current 60 mm focal length technology demonstrator covers ~400 to 800 nm, with ~50 nm instantaneous bandwidth, voltage-tunable center wavelength. We believe further increase in both free spectral range and the image FOV can be achieved in future with further improvements in design, without significant cost impact in production quantity. The lens exhibits high polarized transmission (~70% average), fast switching (<100 ms), good out of band suppression (~20 dB) low power consumption and fully non-mechanical operation. Figure 3 (left) shows polarized transmission measured with a visible wavelength range spectrophotometer. For comparison with traditional multistage birefringent filter designs, polarized transmission at 425 nm is >2X higher than our prior short wavelength optimized demonstration and ~7X better than commercial state of the art, which really suffers from low transmission at shorter wavelengths.

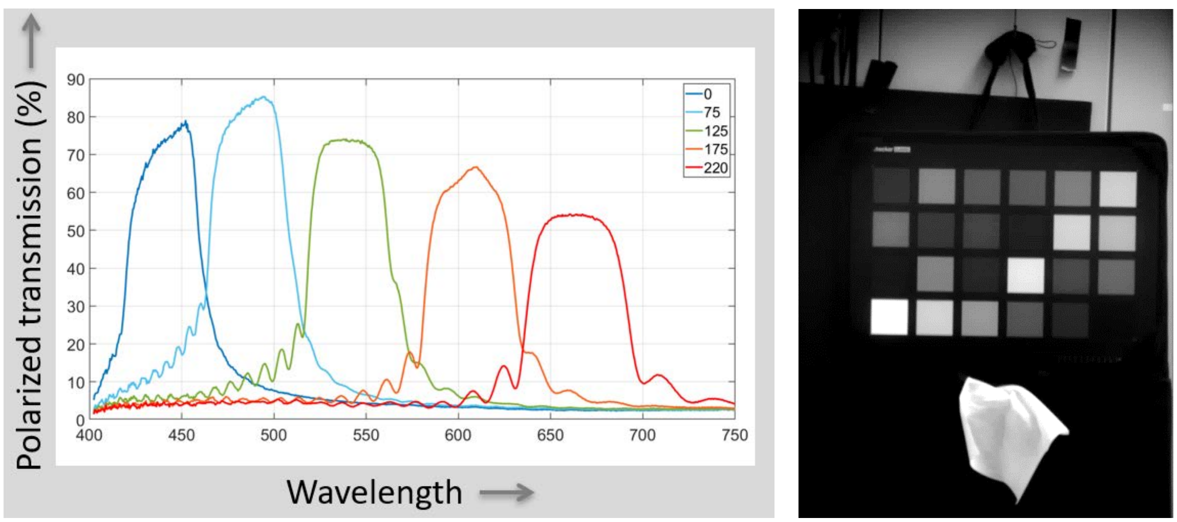


Figure 3 (Left) Polarized transmission as a function of wavelength in the nominally visible range at voltages from 0 to 220V (Right) Device under test imaging a color target.

Dissemination of results will occur over the next several months. We have had discussions with Teledyne business units in the digital imaging segment to investigate potential for transition to a product. Subsequently, we also plan to submit research articles in peer reviewed journals (of interest to optics as well as forensic community) for dissemination to a broad audience.

Main Body of the Final Technical Report

I. Introduction

I.1. Background

Crime scene investigators are tasked with detecting several types of materials present at the scene, including body fluids, hair, fiber, gunshot residue, explosive residue, imprints, glass and metal shards. These are often difficult to distinguish from the background and present a formidable challenge to detect and identify, for example, blood on rust, shoeprints on glossy surfaces, stains on similarly colored backgrounds and textures that create overwhelming clutter. Different materials comprising crime scene evidence of interest have different signatures, and thus require a plethora of techniques for contrast enhancement.

Forensic tools available in the field are considerably limited than in a crime laboratory. Digital single lens reflex (DSLR) cameras, along with powerful image processing tools (e.g., Adobe Photoshop) are extremely valuable in the field [3]. However, a significant amount of manual post-processing work is required for image enhancement, the spectral information is limited to the three bands that human eyes see, and signatures outside the visible spectrum are not captured. Recently, specialized monochrome forensic SLR cameras used in conjunction with optical filters have become available for detection of ultraviolet (UV) and near-infrared (NIR) wavelengths [4]. NIR capability has been shown to be useful in enhancing the visibility of bloodstains, document-forgery, and gunpowder residue [4,5].

Another tool popular among forensic investigators is the alternate light source (ALS), based on arc lamps [6], LEDs [7], or even lasers [8], typically used with a matching set of filters, or simply colored eyewear [6]. UV reflectance has been shown to be useful for fingerprint, bite mark, bruise, and shoeprint identification [9]. A large class of materials (e.g. body fluids) exhibits fluorescence [10, 11]. Extreme oblique angle illumination with ALS is often used to examine light scattered by shoeprints, fingerprints etc. [12]. Polarization signatures have also been shown to be useful in certain scenarios [13].

Current practice in crime scene investigation relies heavily on manual data collection with multiple sensors and laborious post processing in the lab, which is time intensive and restrict rapid location, identification, and quantitative analysis of crime scene data in real time. An electro-optically selected, continuously tunable multispectral imaging tool can enable a versatile and fast image collection. TS&I demonstrated and developed a concept for portable multi-spectral camera systems with powerful backend processing for field triage application through two NIJ funded projects [1, 2]. Breadboard and brass board (see Figure 4) level systems were built and demonstrated of ability to operate with a strobed multi-spectral illuminator, with minimal scene conditioning (not susceptible to background) and even capture fluorescent imagery in presence of indirect sunlight. We also demonstrated a user-friendly GUI for an easy to access enhanced detection using advanced image-processing algorithms on images acquired in multiple spectral bands. See Figure 4.

However, the high cost and complexity of the LCTF (the component that enabled these multispectral imaging hardware and software demonstrations), has been a major impediment to bringing an affordably priced attractive solution to the community.

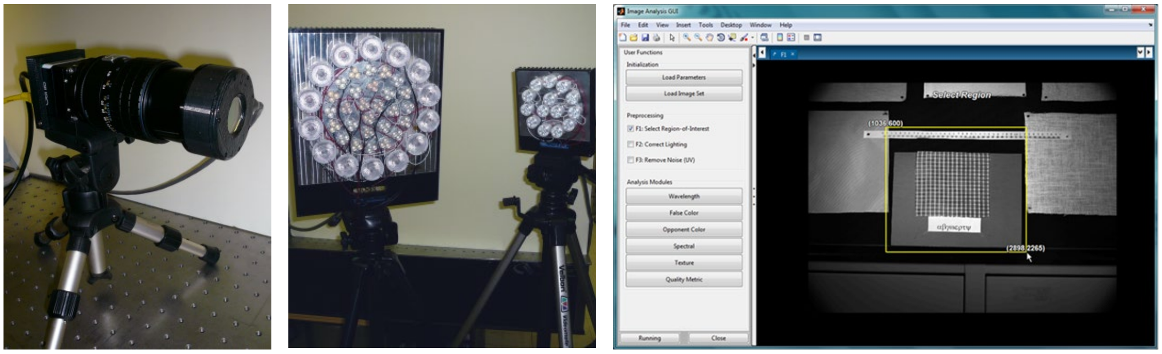


Figure 4 Brass board forensic crime scene survey camera system developed in [2]. Left: camera with LCTF mounted on the lens; Middle: VIS-NIR and UV illuminator; Right: image processing GUI

I.2. Research Rationale

The research was motivated by recent technology advancements at TS&I of a cholesteric liquid crystal (ChLC) tunable filter (ChLCTF) and a novel, elegant and inherently low-cost lens design approach that allows the ChLCTF to be used as a tunable lens. The demonstrator lens can be attached to a conventional off-the-shelf camera with an appropriate mounting adapter (M42) and the spectral band that it images in can be continuously tuned using an applied DC voltage.

The ultimate purpose of the proposed work is to bring to the forensic community an affordable integrated multi-spectral forensic survey camera capable of fast real time imaging and contrast enhancement of target signatures of forensic interest. The camera can be used with multi-wavelength LED illumination in an active imaging mode, along with backend image processing as demonstrated in the earlier efforts.

Our purpose is aligned with the Development Goal of the NIJ’s Research and Development in Forensic Science for Criminal Justice Purposes programs and addresses multiple objectives under this goal. Specifically, the resultant system will highly improve the “front end” of the crime scene survey, alleviate the intense laborious manual data collection, improve the throughput, and minimize the potential for contamination.

Beyond enabling an integrated multispectral forensic imaging system at an affordable cost, we see application for the MultiTuDe lens itself as a tool for other developers for their forensic applications, such as multispectral microscopy and standoff trace detection using SWIR spectroscopy [14,15]. The significantly reduced cost and SWaP (Size, Weight and Power) would even enable dedicated imaging system for small UAV platforms, performing tasks such as land survey and identifying hidden graves [16,17].

II. Methods

II.1. Cholesteric Liquid Crystal Tunable Filter (ChLCTF)

II.1.1. Background

We used a a specially formulated cholesteric liquid crystal (ChLC) cell as the color tuning component at the heart of the multi-spectral imaging lens developed in this work. ChLC materials are composed of self-assembled elongated molecules whose orientation twists periodically in a specific direction, i.e. either left-hand (LH) or right-hand (RH) rotation of the liquid crystal director along a helical axis in space [18]. The cholesteric phase forms naturally in chiral liquid crystalline molecules but is more commonly formulated via chirality transfer from a chiral dopant to a nematic LC host. Because of the extremely regular molecular arrangement and resulted periodic spatial refractive index distribution, they are considered one-dimensional photonic bandgap materials. Optically, the RH or LH structure of CLCs reflects the circular polarized incoming beam with the same handedness when Bragg condition for wavelength is met. Accordingly, only 50% of unpolarized light will be reflected by a single ChLC cell. The reflection notch of CLCs is centered at the wavelength: $\lambda_0 = n_a \times p_0$, where n_a is the average refractive index of the LC and p_0 is the cholesteric helical pitch length [18]. The helical pitch length of a ChLC medium usually is inversely proportional to the chiral dopant concentration in the mixture. Consequently, it is feasible to arrange the helical pitch to match to a desired wavelength from ultraviolet to infrared. The static bandwidth of ChLCs, $\Delta\lambda$, in the visible wavelength, is a few tens of nanometers, typically 50-100 nm, depending on the LC material birefringence, i.e. a product of LC birefringence and cholesteric pitch length, $\Delta\lambda \approx \Delta n \times p_0$. About 15 years ago, the color tuning in ChLC materials were first reported for tunable laser [19] and display [20] applications. In those reported studies, polymer-stabilization technique was used to facilitate the stable electrical tuning of the pitch. We used the same technique for our application.

When an electric field is applied above the threshold voltage, the director of ChLC with negative dielectric anisotropy ($\Delta\varepsilon < 0$) tends to align the nematic directors in a ChLC medium perpendicular to the applied electric field. When a ChLC cell contains both polymer network and LC medium with $\Delta\varepsilon < 0$, a DC field with moderate strength (0-6 V/µm) can induce or tune the center reflection wavelength by 300~400 nm [21]. With tuning, the reflection wavelength shifts to longer wavelength (red tuning) with increasing DC voltage and returns back to original notch position when the electric voltage is switched off. The tuning mechanism is attributed to the deformed polymer network due to the interactions between trapped ion charges and the applied DC field [22,23,24]. Figure 5 illustrates the tuning mechanism of trapped ion charge in a DC field

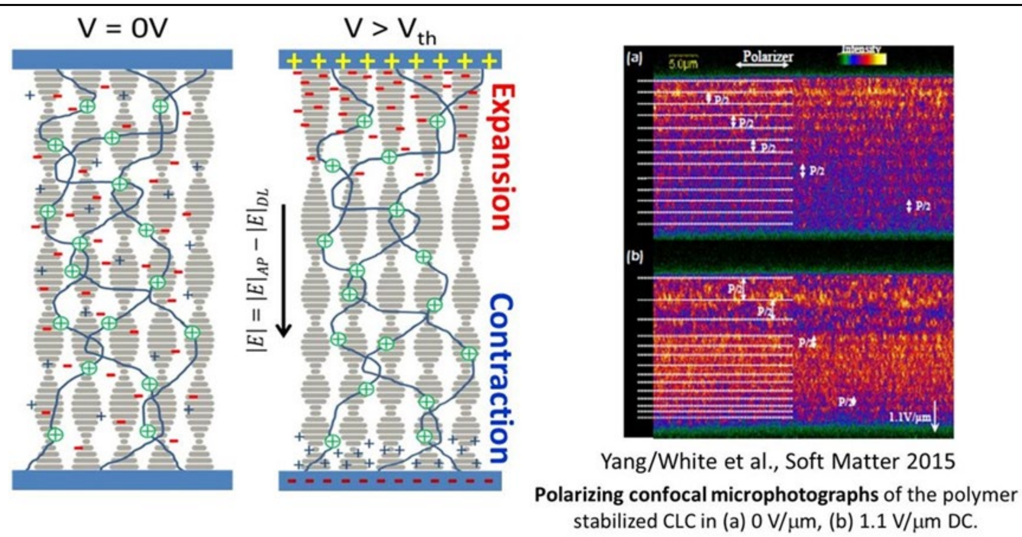


Figure 5 (Left) A postulated tuning mechanism and (Right) the confocal microscopic picture of a polymer stabilized tunable ChLC cell before and after tuning voltage was applied [25]

and the evidence obtained with a polarizing confocal microscope [25].

It is also possible to use LC materials with positive Δε to achieve reflection wavelength tuning, but we used LC host material with negative dielectric anisotropy Δε due to an issue related to the spectral broadening (increased bandwidth and reduced peak reflection) accompanying the tuning effect itself.

It was a challenge to achieve the desired continuous tunability with uniform pitch and no spectral broadening during tuning, particularly at visible wavelengths than at infrared, where material pitch is longer. We overcame this challenge through extensive material and device optimization.

II.1.2. ChLC Fabrication and Measurement

The typical formulation of a tuning polymer stabilized ChC mixture will have the following components: host LC material (for example, MLC 2079 made by Merck), non-reactive chiral dopants (for example. R811 and R5011 made by Merck), reactive mesogen monomer (RM82 made by Merck), chiral reactive mesogen monomer (similar to RM82 but chiral), photo-initiator and a thermal inhibitor. We optimize the relative concentrations to achieve the desired electro-optic pitch tuning performance.

For planar alignment of LC material at the inner surfaces of the ChLC cell, a polyimide layer was spin-coated, baked, and rubbed before the substrates were used to fabricate empty LC cells. Polymerization process is performed after the cell is filled with LC mixture which creates the tunable filter or the ChLCTF.

Figure 6 shows ChLCTF cells fabricated with their center reflection wavelength at zero voltage around 430 nm. The transmission spectra of these cells were measured with an open aperture as the baseline (100%) and a circularly polarized source (the circular polarizer and the ChLCTF cells were not index-matched which exaggerates the insertion loss).

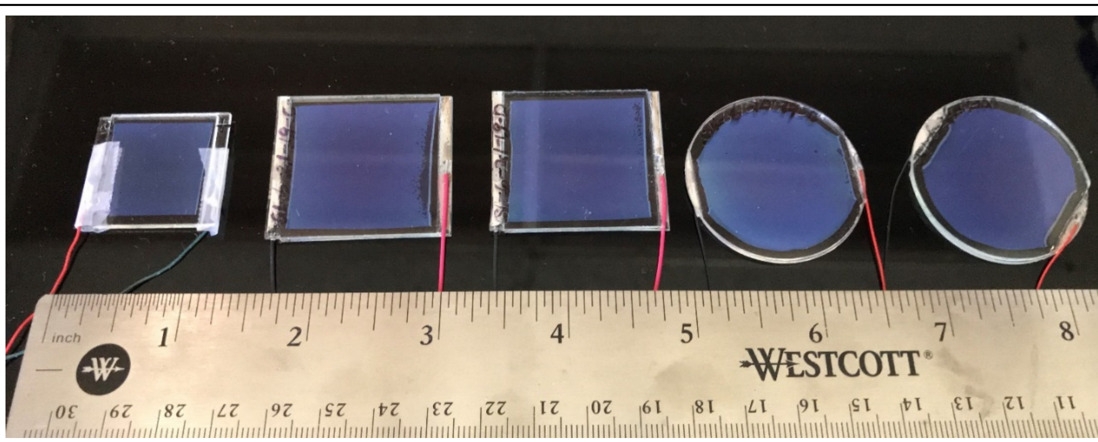


Figure 6 Fabricated tunable ChLCTF cells with zero voltage peak reflection around 450 nm.

Figure 7 shows the tuning transmission spectra of a ChLCTF cell.

We also performed repeatability tests on the cells for short term (single day) as well as long term (6 month) duration.

The ChLCTF cells have good short-term tuning reproducibility with the repeated voltage tuned spectral measurements. Over large time period however, there was a small amount of shift observed which is also a function of voltage (Figure 8). We will continue to investigate this effect in future. Meanwhile, a periodic calibration will restore the spectral accuracy and is an acceptable solution for commercial applications.

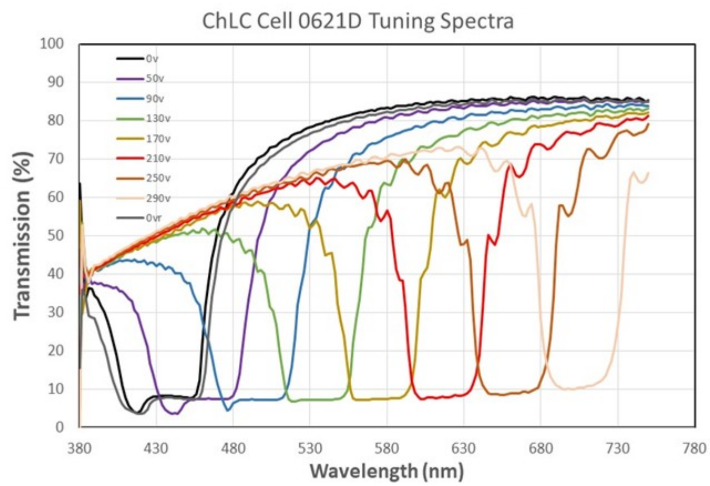


Figure 7 Tuning spectra of a representative ChLCTF cell, measured with an open aperture and through a circular polarizer as the baseline of 100%.

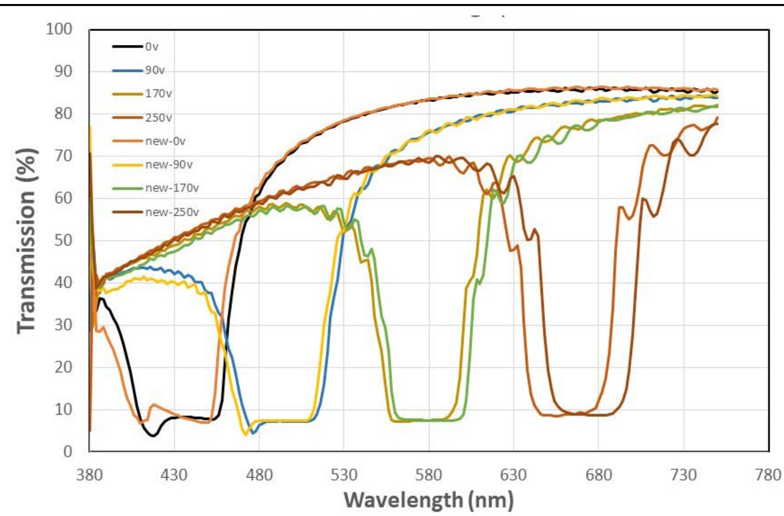


Figure 8 A small voltage dependent shift in the spectral curves six months after the cells were first fabricated (representative example). We anticipate that this shift can be corrected through drive voltage correction and a periodic (>6 month) calibration. More measurements will be performed beyond the current project

II.2. MultiTuDe Lens Optical Design

Figure 9 shows a simplified MultiTuDe lens design concept based on a ChLCTF as the central tuning element. ChLCTF will reflect in-band light with correct circular polarization and transmit all other light.

In the basic concept, a broadband circular polarizer (a combination of linear polarizer and broadband quarter wave plate) selects light of one polarization to be incident on the tunable cholesteric filter. The light transmits with no change due to orthogonal handedness between incident light and cholesteric filter. The primary mirror reflects light and flips the handedness of the reflected light. Now, only a selected spectral band is reflected by the cholesteric filter back towards the camera. The out of band light escapes out and does not reach the sensor. The spectral band can be tuned with voltage. A simplistic design of Figure 9 however will have an extremely limited imaging performance and needed significant optimization.

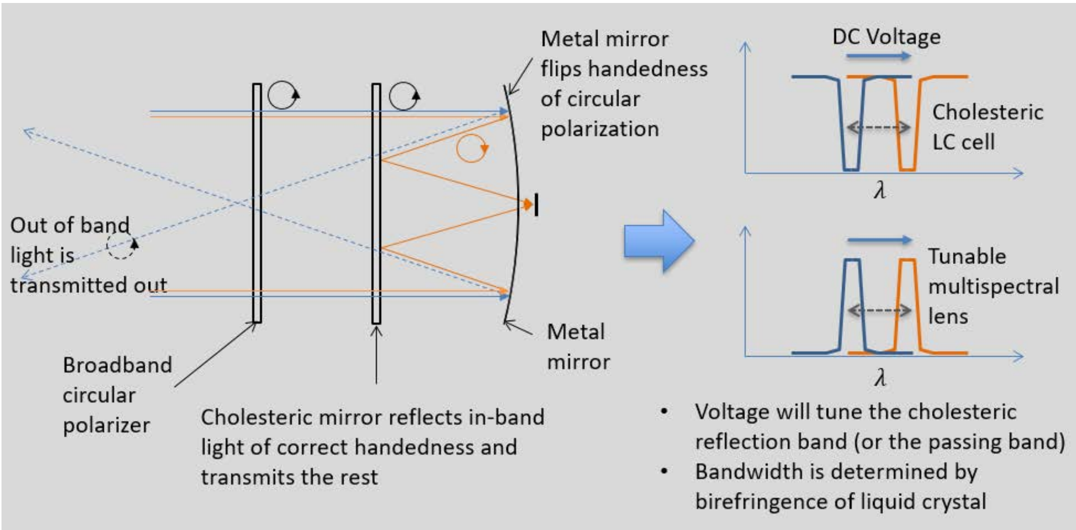


Figure 9 MultiTuDe lens design concept (simplified)

We performed an optical design trade study to develop an optimal design that can maximize the field of view and imaging performance (spot size and image MTF-modulation transfer function) consistent with the selected camera imager (Teledyne DALSA Genie TS-M-4096 12 MP 4096×3072). The design constraint is that it retains the focus over the entire spectral bandwidth. We also limited the maximum angle rays can subtend at the ChLCTF to be < 15° to minimize spectral shifts and maintain high spectral contrast.

The design options investigated in the trade study included conversion to a refractive form (unsuccessful) and several enhancements in the reflective form. We investigated Mangin mirror, doublet with Mangin mirror, and a mix of refractive elements in addition to reflective mirror and adding aspheric coefficient to one or more surfaces. Designing for a moderate 10° field of view allowed us to limit the number of aspheric elements needed (and control the cost of custom optics in prototype quantity). Larger field of view could be achieved in future with a more complex optical design, with minimal impact on cost, in production quantity.

Figure 10 shows raytrace diagrams for some of the alternate options examined. We began with exploring an expanded design space with primarily refractive elements with the cholesteric element incorporated in between hoping to achieve very large field of view. This approach proved not feasible due to constraints of the polarization optics, and we reverted to reflective catadioptric designs with curved primary mirror. After a couple more design iterations, we converged on a design that was compatible with the size on cholesteric LC element, as well as with mechanical requirements of the camera mount. In the process we added two custom lens elements that improved the MTF performance as well. This design has an effective focal length of ~60 mm and can support ~10° FOV.

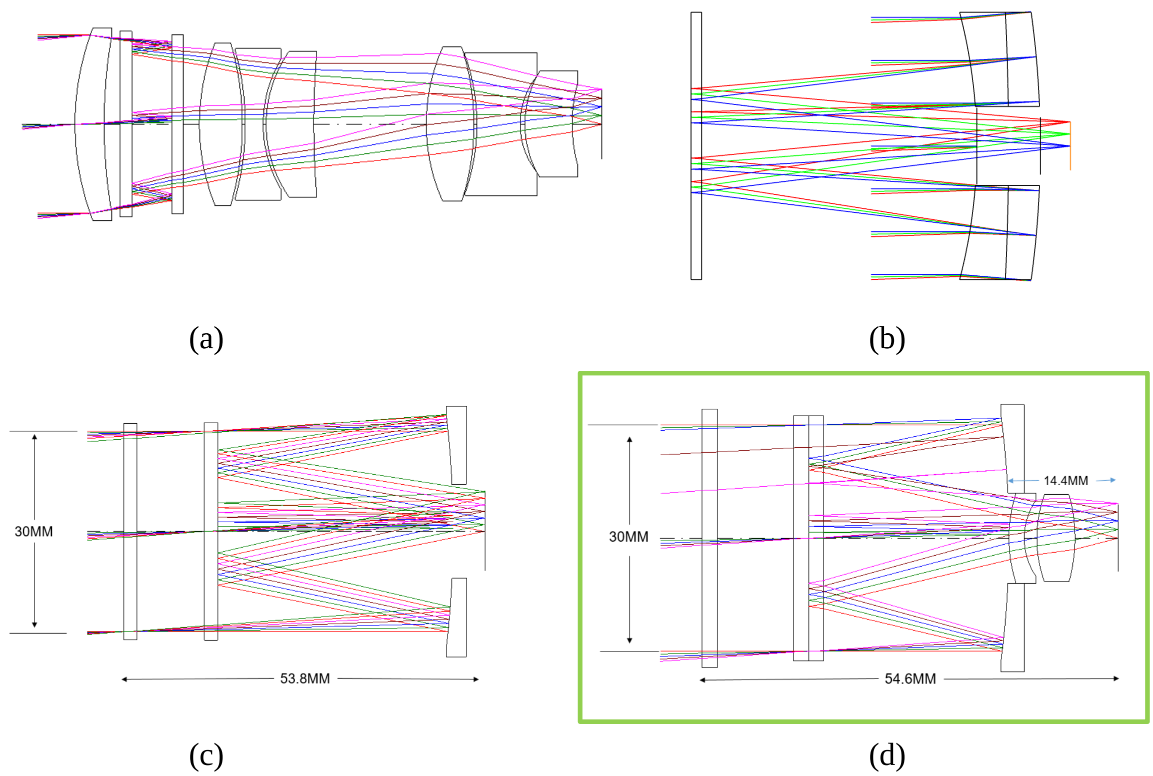


Figure 10 Optical design investigation and optimization (a) Refractive implementation: Polarization issues made this not practical (b) Catadioptric design with Mangin mirror doublet (c) Aspheric primary provided better performance, focal plane needed to be moved farther back to meet camera requirements (d) Optimized design compatible with the size constraint on cholesteric LC element as well as with mechanical requirements of the camera mount, in the process the two refractive lens elements used to further improve the MTF/FOV.

II.3. Optomechanical Package Design and Assembly:

We took a modular approach to opto-mechanical design. We divided the imaging system into three sub-assemblies. See Figure 11. 1) Liquid crystal-based wavelength tunable front end; 2) conventional optical sub-assembly in the middle with the lenses and the mirror; and 3) the camera and M42 mount at the back end. The first two sub-assemblies form the lens and the third is the camera. The front and the mid assemblies could be integrated independently.

We tested two variations of the front assembly: one with an off the shelf circular polarizer and the second where we created a broadband circular polarizer with an off-the-shelf broadband quarter waveplate and a liner polarizer. The second approach was significantly better in terms of spectral contrast and was down-selected.

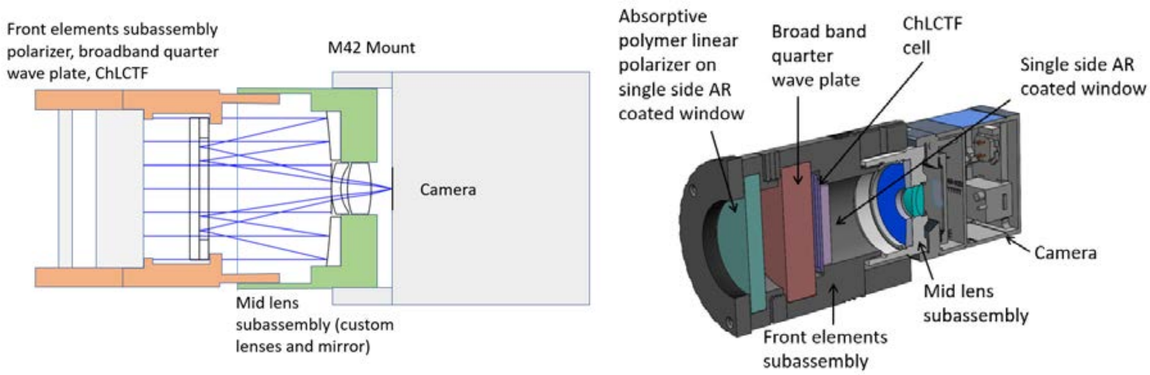


Figure 11 (Left) Modular approach to opto-mechanical design of the imaging system (Right) Cross section of the solid model

The mid sub-assembly consisted of the custom aspheric reflector with a metal coating, and two custom spherical lenses, assembled with high precision mechanical tolerances.

II.4.Lens Integration and Test

The integration of the three subassemblies was straightforward. We used a color target for integration and initial qualitative test. The only active alignment in the lens was focus adjustment, which we performed using the threads between the mechanical subassemblies. We applied voltage through the ruggedized connector mounted on the package to control the spectral response and used direct feedback from the live camera imagery to optimally focus the lens and complete the alignment. The focus is independent of wavelength and needs to be adjusted only based on target distance. Color targets while somewhat intuitive rely on visual response of the human eye, and the actual spectral content is much broader than the instantaneous bandwidth of the MultiTuDe lens. Thus, we switched over to spectrophotometer measurements for quantitative characterization. See

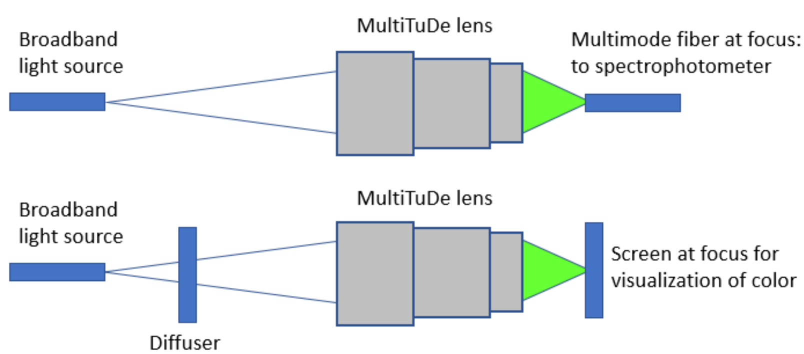


Figure 12 (Top) Broadband light source and spectrophotometer for quantitative transmission measurements and (Bottom) visualization of transmitted color as a function of voltage

Figure 12. We also used a screen with broadband light source for visualization of color transmitted by the lens as a function of applied voltage.

For the purpose of these demonstrations, we used a laboratory power supply to drive the device. It should be noted that although the operating voltage is high (up to 215 V), the load is capacitive and draws very low current and can be implemented with a compact form factor.

III. Results

Figure 13 (top) shows lens imaging tests using a color target with different voltages applied to the filter. The focal plane itself is monochrome. The lens shows good image quality and the lens discriminates colors based on the applied voltage. The spectral content of the color target is much broader than the 50 nm bandwidth of the filter, but it can be clearly seen as marked in the image that when the lens is in green (125V) state, red square transmission is significantly diminished and vice versa when the lens is in red (215V) state.

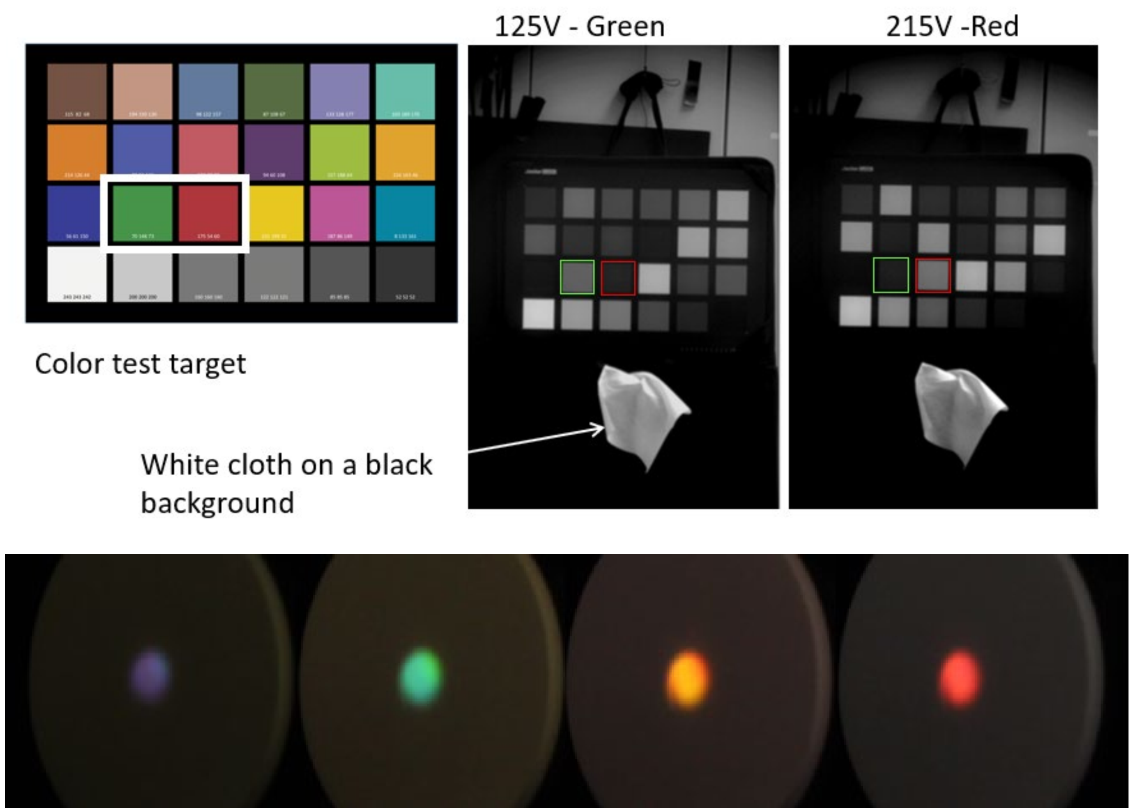
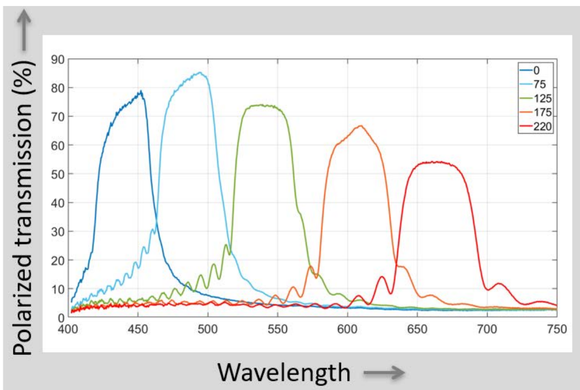


Figure 13 (Top) MultiTuDe lens imaging of a color target shows good image quality as well as electrically tuned filter function, e.g. in the figure, at 125V it transmits green and suppresses other colors (e.g. the highlighted red square), and at 215V it transmits red and suppresses other colors (e.g. the highlighted green square). (Bottom) is a sequence from a video of the light transmitted through the lens and captured on a screen, as the voltage is scanned from 0V to 220V, or from blue to red, captured by a color camera.

Figure 13 (bottom) captured images of transmitted light without the focal plane is much more intuitive to interpret. It shows screen shots from a video of the light transmitted through the lens and captured on a screen per Figure 12 (bottom), as the voltage is scanned from blue to red captured by a color camera. The intensity variation is due to intensity variation of the broadband source itself which peaked near green.

For more quantitative measurement of the spectral response, the transmitted light was characterized by a spectrophotometer. The spectrophotometer response as a function of voltage (normalized to effective aperture without a lens to show absolute polarized transmission) is shown in Figure 14.



Spectral Range	400 - 800 nm
Instantaneous Bandwidth	50 nm
Polarized transmission	70% (average)
Switching time	< 200 ms
Focal length	60 mm
Field of view	10°
Out of band suppression	20 dB (average)

Figure 14 (Left) Polarized transmission as a function of wavelength in the nominally visible range at voltages from 0 to 220V (Right) Nominal lens specifications.

IV. Conclusions and Next Steps

The project met its goal through the successful demonstration of a novel, unique and inherently low-cost lens design for multispectral imaging. It addressed the cost and complexity problem in the multispectral forensic camera concept we demonstrated in the earlier grants.

In terms of next steps, further improvements to the optical design to increase FOV are feasible. Material improvements and potential alternative [26] to improve speed are also feasible. While switching speed is comparable with off-the-shelf solutions, further improvement is clearly desirable from product perspective. Other steps include detailed characterization of material aging, calibration, and design of a compact controller.

A potential product can be envisioned either as a complete camera system, or just the multispectral lens that can work with off-the-shelf cameras, or as a microscope accessory. LC based multispectral imaging products already exist [27,28], and we believe the inherently low-cost nature and higher transmission of our lens design offers a significant advantage in terms of acceptance and utility to the practitioners.

V. Dissemination of Research Findings

The dissemination activity for this project has just begun. We have had multiple internal discussions with Teledyne business units in the digital imaging market segment to investigate potential transition to a product within Teledyne. Subsequently, we also plan to submit research articles in peer reviewed journals (of interest to optics as well as forensic community) for dissemination to a broad audience. While our projects have generally focused on forensic applications, the unique approach to multispectral lens design will be of high interest to the optical design community as well and may inspire applications outside of forensic field as well. In addition, we provided an informal update in telephone discussion with our points of contact at Forensic Technology Center of Excellence at RTI international.

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