Single-Point Detection Architecture via Liquid Crystal Modulation for Hyperspectral Imaging Systems

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ABSTRACT Hyperspectral imaging (HSI) architectures can acquire one-dimension of spatial information and one-dimension of spectral information on a two-dimensional image sensor for an image, such as in the traditional line-scan HSI architecture. However, development of HSI architectures for multiple spatial dimensions is challenging as there is not a third dimension on a two-dimensional image sensor on which to store spectral information. The presented work introduces a snapshot HSI architecture to alleviate this issue. The snapshot HSI architecture incorporates single-point detection via liquid crystal modulation and a single photodiode. Mixing of hyperspectral data is expressed as intermodulation frequency products within the Fourier-domain. Spatial information can be recorded through spatial frequencies and spectral information can be recorded through spectral frequencies. Such modulation is achieved through liquid crystal spatial and spectral arrays of an image beam. The spatial and spectral modulation frequencies form intermodulation frequency products that are recorded on the single photodiode and can be uncovered through Fourier-domain filtering.

INDEX TERMS Frequency-domain analysis, multispectral imaging, optical diffraction, photodiode.

I. INTRODUCTION Digital imaging systems are ubiquitous in everyday life, being deployed for applications in many sectors. The biomedical sector uses digital imaging systems for diagnostics in histology [1]. The defence and security sector uses digital imaging systems for surveillance [2]. Industrial manufacturing sectors uses digital imaging systems for machine vision applications [3]. The extensive use of digital imaging systems can be attributed to the low cost and high spatial resolution of image sensors, such as, charged coupled device (CCD) arrays [4].

To achieve this extensive use of digital imaging systems, the technology progressed over time to collect more and more information. Single-point measurements, from a photodiode, detect the magnitude of light over a single spatial dimension [5]. Gray-scale imaging captures the magnitude of light at many points over two spatial dimensions [6]. Colour imaging, similar to that of gray-scale imaging, measures the magnitude of incident light via three broad colour channels (i.e., red, green, and blue) [7]. Digital imaging systems are suitable for real-time imaging applications where image capture and analysis must occur quickly [8], however, they typically do not collect spectral information (beyond nominal spectral information of red, green, and blue light).

Mirroring the development of digital imaging systems, spectroscopy systems have been developed and established in research and other applications. Spectroscopy systems are used in various applications, including crop harvest monitoring [9], quality control of biodiesel production [10], and mechanical properties assessment of synthetic biomaterials [11]. Spectroscopy systems traditionally operate with a single point capturing an entire spectrum.

In recent years, efforts have been made to merge digital imaging systems with spectroscopy systems. Such efforts manifest themselves as hyperspectral imaging (HSI) architectures—allowing for the concurrent measurement of spectral (wavelength) and spatial information. A CCD image sensor is used to measure and map spectral and spatial
information into a hypercube, being a three dimensional datacube structure. The hypercube mapping scheme depends on the traits of the HSI architecture being deployed.

Hyperspectral imaging architectures exist in a variety of forms: point-scan [12], line-scan [13], and wavelength-scan [14]. These HSI architecture categories are defined by the technique used to map the measured image dimensions (i.e., spatial dimensions, \(X_{\text{image}}, Y_{\text{image}},\) and wavelength, \(\lambda\)) to the physical dimensions of image sensor (i.e., \(X_{\text{sensor}}, Y_{\text{sensor}}\)) for construction of the hypercube. These mapping techniques are a prerequisite of every HSI system to overcome the fundamental challenges.

Each of the aforementioned HSI architectures solve this fundamental HSI challenge by mapping one of the image dimensions to the image sensor as time—necessitating prolonged and unsuitable acquisition times for real-time imaging applications. To address this fundamental challenge, researchers have begun to investigate snapshot HSI architectures [15], some of which encode and superimpose the third image dimension onto a dimension of the image sensor that is already in use [16], [17]. For example, our previous work presented an HSI architecture with the potential for a hypercube that mapped \(X_{\text{image}}, Y_{\text{image}},\) and \(\lambda\) to \(X_{\text{sensor}}, Y_{\text{sensor}},\) and \(F,\) where \(F\) is a modulation frequency [18].

It is desirable to eliminate the sensor dimensions altogether as this avoids increased image acquisition times (CCD frame-transfer interval increases with sensor-pixel-array dimensions [19]). An improvement of interest is to consolidate the sensor imaging pixels to utilize a single sensing element [20], [21]. This can be made possible through the use of high-speed optical modulators, such as liquid crystal (LC) shutters [22]. This is the focus of the presented work.

In this work, we propose a snapshot HSI architecture that uses one set of LC shutters (i.e., LC pixels) for \(X_{\text{image}}\) and \(Y_{\text{image}}\) mapping to a modulation frequency, \(F_{\text{spatial}},\) and another set of LC shutters for and \(\lambda\) mapping to another modulation frequency, \(F_{\text{spectral}}.\) This basic principle of operation is shown in Fig. 1.

The proposed work can be discussed in relation to LC compressive approaches [23]–[25]. Such work involves reducing the large amount of hyperspectral data to be stored through compressive techniques and can reduce data storage by an order of magnitude. Such a technique relies on modulating the signal by a tunable optical thin film structure. Several modulation functions are applied at once and together produce the spectrum, through low mutual coherence. Our work has similarity, involving the use of modulation albeit through Fourier analyses rather than low coherence, with the spectrum appearing in a sideband of sum or difference terms. However, our work does not require the use of phase information, and relies solely on amplitude information in the Fourier domain.

The proposed work can also be discussed in relation to other snapshot hyperspectral imaging techniques. The Fabry-Perot etalon approach [26]–[28] can be discussed. Here, a fast light modulator is used. This technique is complicated, relative to our use of LC shutters, given that it makes use of broadband laser emission. Filter array techniques can also be noted [29]–[33]. Here, a mosaic of filters are arranged consecutively before a photometer. However, such a system requires integration of complicated optical components. Nanophotonic techniques [34], [35] can also be discussed. In these systems, an array of photodectors is used which are at the micro- or nano-scale. Such a device must use photonic crystals and use multipath to increase interaction length and distinguish phase and relies on compressive sensing to recover the spectra.

In this manuscript, the snapshot HSI architecture is developed in terms of its geometry, theoretical operation, and its experimental operation. Experimental considerations are discussed in terms of harmonic mitigation.

II. GEOMETRY

The fundamental geometric design of our snapshot HSI architecture is shown in Fig. 2. An image beam is directed onto and modulated by the first array of LC pixels, being the spatial LC pixels (\(i = 1, 2, 3, \ldots, m\)). (Fourier frequency analyses will subsequently reveal information corresponding to these spatial LC pixels.) The now spatially-modulated
image beam interacts with a diffraction grating. (A binary amplitude diffraction grating or a blazed diffraction grating could be used.) The first order diffraction pattern (i.e., the spectrum) of the image beam corresponding to each spatial position \((i = 1, 2, 3, \ldots, m)\) is concurrently directed through and modulated by the second array of LC pixels, being the spectral LC pixels \((j = 1, 2, 3, \ldots, n)\). The spatial \((i = 1, 2, 3, \ldots, m)\) and spectral \((j = 1, 2, 3, \ldots, n)\) LC pixel arrays are both extended into a second dimension (seen in Fig. 1), that is \((k = 1, 2, 3, \ldots, p)\) to structure a pair of LC pixel matrices which enable the acquisition of 2D spatial image beams. (Fourier frequency analyses will subsequently reveal information corresponding to these spectral LC pixels.) The image beam can subsequently be focused onto a single photodiode (seen in Fig. 1) for measurement of the intermodulation frequency products (i.e., the sum and difference frequencies). The time-domain output from the single photodiode can undergo Fourier-domain frequency analyses with frequencies \((\text{frequencies})\). The time-domain output from the single photodiode (seen in Fig. 1) for measurement of the intermodulation frequencies are chosen with narrow frequency spacing. The intermixing between spatial and spectral modulation frequencies produces symmetric upper sideband (USB) and lower sideband (LSB) intermodulation frequency products (i.e., intermodulation frequency peaks), being represented by respective red and black peaks. Through Fourier-domain frequency analyses, a filter bank can be applied to isolate either the USBs or LSBs. Fig. 3 shows such a filter for the case of spatial LC pixel \(i = 2\) and \(j = 1, 2, 3, \ldots, n\) spatial LC pixels. This data represents the spectrum for spatial LC pixel \(i = 2\).

The Fourier amplitude frequency response of Fig. 3 is generated for the \(j^{\text{th}}\) spatial LC pixel and the \(j^{\text{th}}\) spectral LC pixel as follows. Unmodulated light, \(I_0\), originates from an image beam. The unmodulated light is modulated by the \(j^{\text{th}}\) spatial LC pixel at a frequency of \(F_i\) (being previously noted as \(F_{\text{spatial}}\)) to become,

\[
I_{\text{spatial}} = I_0 (1 + \cos (2 \pi F_i))
\]  

(1)

This light is then modulated by the \(j^{\text{th}}\) spectral LC pixel at a frequency of \(F_j\) (being previously noted as \(F_{\text{spectral}}\)) to become,

\[
I_{\text{spectral}} = I_{\text{spatial}} (1 + \cos (2 \pi F_j)).
\]  

(2)

This output light forms intermodulation frequency products described as

\[
I_{\text{intermod}} = I_0 \left(1 + \cos (2 \pi F_i) + \cos (2 \pi F_j) + I_{\text{intermod}}\right)
\]  

(3)

where the intermodulation term is,

\[
I_{\text{intermod}} = \frac{1}{2} \cos (2 \pi (F_i - F_j)) + \frac{1}{2} \cos (2 \pi (F_i + F_j)).
\]  

(4)

The first and second terms of the intermodulation term, (4), are the respective difference and sum frequencies which form the components of the respective lower and upper sidebands. In this way either the lower or upper sidebands contain the entire information needed to construct the spectra for a given spatial LC pixel.

III. THEORETICAL OPERATION

To enable the fundamental operation of the snapshot HSI architecture, appropriate spatial and spectral frequencies must be chosen. Fig. 3 shows the Fourier amplitude frequency response for the case where spatial modulation frequencies are chosen with wide frequency spacing and spectral modulation frequencies are chosen with narrow frequency spacing. The intermixing between spatial and spectral modulation frequencies produces symmetric upper sideband (USB) and lower sideband (LSB) intermodulation frequency products (i.e., intermodulation frequency peaks), being represented by respective red and black peaks. Through Fourier-domain frequency analyses, a filter bank can be applied to isolate either the USBs or LSBs. Fig. 3 shows such a filter for the case of spatial LC pixel \(i = 2\) and \(j = 1, 2, 3, \ldots, n\) spatial LC pixels. This data represents the spectrum for spatial LC pixel \(i = 2\).

The Fourier amplitude frequency response of Fig. 3 is generated for the \(j^{\text{th}}\) spatial LC pixel and the \(j^{\text{th}}\) spectral LC pixel as follows. Unmodulated light, \(I_0\), originates from an image beam. The unmodulated light is modulated by the \(j^{\text{th}}\) spatial LC pixel at a frequency of \(F_i\) (being previously noted as \(F_{\text{spatial}}\)) to become,

\[
I_{\text{spatial}} = I_0 (1 + \cos (2 \pi F_i))
\]  

(1)

This light is then modulated by the \(j^{\text{th}}\) spectral LC pixel at a frequency of \(F_j\) (being previously noted as \(F_{\text{spectral}}\)) to become,

\[
I_{\text{spectral}} = I_{\text{spatial}} (1 + \cos (2 \pi F_j)).
\]  

(2)

This output light forms intermodulation frequency products described as

\[
I_{\text{intermod}} = I_0 \left(1 + \cos (2 \pi F_i) + \cos (2 \pi F_j) + I_{\text{intermod}}\right)
\]  

(3)

where the intermodulation term is,

\[
I_{\text{intermod}} = \frac{1}{2} \cos (2 \pi (F_i - F_j)) + \frac{1}{2} \cos (2 \pi (F_i + F_j)).
\]  

(4)

The first and second terms of the intermodulation term, (4), are the respective difference and sum frequencies which form the components of the respective lower and upper sidebands. In this way either the lower or upper sidebands contain the entire information needed to construct the spectra for a given spatial LC pixel.

IV. EXPERIMENTAL OPERATION

To achieve fundamental operation of the snapshot HSI architecture, the theoretical framework should be considered alongside a fundamental physical implementation. This physical implementation can illustrate the interaction potential between harmonics and intermodulation frequency products in the Fourier-domain. In this effort, we demonstrate experimental operation of the snapshot HSI architecture for the principal case of the physical implementation where a single spatial LC pixel \(i = 1\) and spectral LC pixel \(j = 1\) are used. The optical modulation for the spatial and spectral LC pixels is performed by a pair of transmissive LC shutters. This transmissive TN type, single pixel, LC shutter was purchased from Digi-key Electronics (part number: 1528-2516-ND), with an operating drive voltage range of 3-5 V. The LC pixel shutters are oriented along the same optical axis—driven...
by two phase-matched sinusoidal voltage waveforms, corresponding to frequencies \( F_i \) and \( F_j \) forming \( f_{\text{spatial}} \) and \( f_{\text{spectral}} \), respectively. A monochromatic image beam is projected into both LC shutters and measured by a photodiode (Thorlabs DET36A). The observed intermodulation frequency products resulting from \( F_i = 90 \) Hz, and \( F_j = 40 \) Hz are shown on Fig. 4(a) as the consequent LSB and USB frequencies, being \( F_{i-j} = 50 \) Hz and \( F_{i+j} = 130 \) Hz. These intermodulation frequency products are observed to have approximately the same magnitude (−37 dB); having symmetrical magnitudes for LSB and USB is consistent with the derived theoretical operation for the snapshot HSI architecture.

In this case, the frequency of the LSB and USB intermodulation frequency products, \( F_{i-j} \) and \( F_{i+j} \), do not interfere with the second harmonic frequency \( (2F_j) \) of the spatial LC pixel shutter for \( i = 1 \).

Avoidance of interference is essential for delineating the correct wavelength intensity for a given spatial LC pixel. In particular, for cases where the spatial modulation frequency spacing, \( \Delta F_i = F_{i+1} - F_i \), is on the order of the spectral modulation frequency spacing, \( \Delta F_j = F_{j+1} - F_j \), the spacing between spectral modulation frequencies should be carefully chosen to not be integer multiples. This situation shown in Fig. 4(b), where \( F_i = 90 \) Hz, and \( F_j = 30 \) Hz. Here we see that \( F_{i-j} = 2F_j \), which manifests as overlap (i.e., interference) of these amplitudes (−29 dB). This creates an asymmetry between frequencies of \( F_{i-j} = 60 \) Hz and \( F_{i+j} = 120 \) Hz. This is undesirable and should be avoided.

To demonstrate the HSI system primary functionality of multiple spatial pixel operation, we demonstrate experimental operation with multiple spatial pixels \( (i = 1, 2) \) with multiple wavelengths (centre wavelengths of 465 nm and 630 nm) overlapped on a spectral pixel \( (j = 1) \). These results are presented in Fig. 4(c) show the HSI resolution of these two separate amplitudes, despite the conflicting overlap on the same spectral pixel. It can be seen that proof-of-concept multi-pixel operation is demonstrated. Two spatial LC pixels are incident with blue 465 nm and red 630 nm LED light which are modulated at frequencies of \( F_{i1} = 90 \) Hz and \( F_{i2} = 180 \) Hz, respectively. The upper sideband (USB) and lower sideband (LSB) intermodulation frequency products are shown, for each spatial pixel \( (i = 1, 2) \), as indicated by \( F_{i1} \pm F_j \) and \( F_{i2} \pm F_j \), with \( F_j = 40 \) Hz.

**V. SIMULATION**

An experimentally-seeded simulation is presented to show the operation of the snapshot HSI architecture. The simulation incorporates four unique LED spectra (i.e., blue 465 nm, yellow 597 nm, red 630 nm, and white) that are obtained using a Thorlabs CCS200 spectrometer and shows the modulated spectra (Fig. 5). These spectra are used as the initial reference image for this simulation, in a two-by-two configuration, with each spectra being associated with a unique spatial LC pixel, as shown in Fig. 6 (in black curves). The spectra incident

![Figure 4](image-url)

**FIGURE 4.** (a) The snapshot hyperspectral imaging architecture’s experimental liquid crystal operation is shown for the principle case of \( i = 1 \) and \( j = 1 \), spatial and spectral liquid crystal pixel shutters having modulation frequencies \( F_i = 90 \) Hz and \( F_j = 40 \) Hz, respectively. The second harmonic frequency for the spectral liquid crystal pixel is shown as \( 2F_j \). The optical mixing between \( F_i \) and \( F_j \) leads to the matching lower sideband and upper sideband intermodulation frequencies, given as \( F_{i-j} \) and \( F_{i+j} \). There is no interference between the second harmonic frequency and the lower sideband, that is, \( F_{i-j} \neq 2F_j \). (b) The snapshot hyperspectral imaging architecture’s experimental operation is shown for the principle case of \( i = 1 \) and \( j = 1 \), spatial and spectral liquid crystal pixel shutters having modulation frequencies \( F_i = 90 \) Hz and \( F_j = 30 \) Hz, respectively. The second harmonic frequency for the spectral liquid crystal pixel is noted as \( 2F_j \). Again, the optical mixing between \( F_i \) and \( F_j \) leads to the matching lower sideband and upper sideband intermodulation frequency products, given as \( F_{i-j} \) and \( F_{i+j} \). Interference is observed between the second harmonic frequency and the lower sideband, since \( F_{i-j} = 2F_j \). (c) Successful multi spatial pixel operation is shown for the snapshot hyperspectral imaging architecture. Spatial liquid crystal shutters, \( i = 1, 2 \), have modulation frequencies \( F_{i1} = 90 \) Hz and \( F_{i2} = 180 \) Hz. The spectral liquid crystal shutter, \( j = 1 \), has a modulation frequency of \( F_j = 40 \) Hz. Intermodulation frequency peaks occur for the case of \( F_{i1} \pm F_j \) being 50 Hz and 130 Hz; as well as, the case of \( F_{i2} \pm F_j \) being 140 Hz and 220 Hz, respectively for both cases.
and spectral pixels are as follows. The pitch of the diffraction grating, spatial pixels, 

diffraction effects are simulated for the geometric parameters being superimposed onto a single spectral LC pixel, demon-

strating the operation of the snapshot HSI architecture. These 
diffraction effects are simulated for the geometric parameters as follows. The pitch of the diffraction grating, spatial pixels, and spectral pixels are \( a_1 = 1 \text{ \(\mu\)m}, a_2 = 40 \text{ \(\mu\)m}, \) and \( a_3 = 40 \text{ \(\mu\)m}, \) respectively. There is a \( c = 10 \text{ cm} \) distance between the spatial and spectral LC pixels, such that, a maximum wavelength range of 250 nm to 950 nm would be captured by a lens and focused onto a single photodiode. The lateral distance between the \( i = 1 \) spatial LC pixel (i.e., \( x_i = 1 \)) and the \( j = 1 \) spectral LC pixel (i.e., \( x_j = 1 \)) is denoted as \( b \).

Using a Cartesian coordinate system and in reference to the Fig. 2 schematic, the angle of diffraction for incident spatial LC pixel spectra is calculated for projection onto the spectral LC pixels using \( \theta_{\text{diff}} = \tan^{-1}[ (x_j - x_i)/(y_j - y_i) ] \). Interpolation is performed as required to ensure projected spectra as a function of \( j \) pixels can be obtained and transformed into corresponding wavelength values using the equation, \( \lambda_{i,j} = a_1[1 - \sin(\theta_{\text{diff}})] \). The time-domain modulation is performed as described by the equations for \( I_{\text{s spatial}} \) and \( I_{\text{spectral}} \) being (1) and (2), respectively. The amplitude of the modulated spectra, as measured by a single photodiode, is summed over time and de-multiplexed with the Fourier transform. A filter bank is used to separate the spectra into upper sideband (USB) and lower sideband (LSB) intermodulation frequency products, as initially illustrated by Fig. 3, and results of the simulation are presented in Fig. 5 for the LSB results and Fig. 6 for the results (grey curves) converted into a function of wavelength through the geometric equation of diffraction. There is an evident similarity between the curves, and this shows the correct operation of the snapshot HSI architecture. Figure 5 shows the intermediate transformation between input and output spectra as a function of wavelength, showing a large peak at the rightmost frequency. This is the result of the \( i = 1, 2, \ldots, m \) frequencies that are still present in the signal. These peaks are shown on Fig. 3. The initial and final spectra from the HSI simulation (Fig. 6) are comparable. This result is significant as it validates that the Fourier based architecture, in principle, can be used to perform single pixel snapshot HSI with acceptable performance.

The theoretical operation of our HSI architecture was evaluated within a computer simulation environment. This simulation was performed under the assumption that the limiting operating parameter for hyperspectral acquisition time was the modulation scheme itself. The maximum duration of modulation for all pixels can be found using the \( T_{\text{max}} = 1/f \) relationship. That is, the pixel modulating at the lowest frequency, corresponding to peak \( j = 1 \) (see Fig. 3), is used to find the longest modulation time. The spatial, spectral, and sum/difference modulation frequencies are evenly spaced within the Fourier domain at a known frequency interval \( \Delta F \), with the total number of frequencies used in this architecture being related to the wavelength range being measured. Because of this, the \( T_{\text{max}} \) parameter increases for a larger wavelength range and decreases for a shorter wavelength.
range. Additionally, the $T_{\text{max}}$ parameter increases for lower $\Delta F_j$ frequency intervals and is decreased for higher $\Delta F_j$ frequency intervals.

The modulation acquisition time, $T_{\text{max}}$, required for high resolution spectral reconstruction for multiple spatial LC pixel operation was found to be 5 and 16 seconds for a wavelength range of 400 to 800 nm and 250 to 950 nm, respectively. Using the results of the experimentally-seeded simulation for the snapshot HSI architecture, we have provided a comparison to conventional and similar systems. Specifically, conventional image dividing type snapshot HSI systems, like that of the image mapping spectrometer (IMS) operate with acquisition times of approximately 10 seconds [36]. Therefore, our snapshot HSI architecture compares favorably.

The operation of this HSI architecture could potentially be affected by sources of error. Proper alignment of the spatial and spectral LC shutters is critical to the functionality of this architecture. The mapping of intermodulation frequency products to wavelength is to be predetermined and unchanged for a working prototype. If a LC shutter were to be misaligned, the wavelength reconstruction would not accurately correspond to the incident wave-front spectra. Furthermore, the amplitude of the reconstructed spectra would be dependent on the wavelength, polarization state, and incident angle, light transmission characteristics of the LC shutters. The LC spatial light modulators (SLM) to be used in a future prototype should be well characterized and accounted for in subsequent prototype development.

The diffraction grating will lose some optical power to the zeroth lobe and to the unused lobes. However, as noted above different choices of diffraction gratings (e.g., a blazed diffraction grating) can reduce this loss of optical power. Additionally, the modulation can lose some optical power. For example, the liquid crystal shutters block and unblock the optical power with their modulation. Additionally, not all optical power goes into the intermodulation peaks. The $i = 1, 2, \ldots, m$ frequencies are still present, as seen in Figures 3, 4, and 5.

The optical throughput could be (roughly) estimated as the product of efficiency terms for the diffraction grating (e.g., approximately fifty percent), LC shutters duty cycle of modulation (e.g., approximately fifty percent each), and glass lenses (e.g., approximately ninety percent). This would produce a rough estimate for efficiency of greater than 10 percent. While low, we believe this is sufficient for many applications.

In future works, the incorporation of this HSI architecture concept into a working prototype would require careful component selection to ensure the optical efficiency is sufficient for the desired application. This above rough estimate can help with this process of application selection.

In our system, additional LC pixels can be added as needed. The arrangements of these pixels can be in a row, but can also include additional rows below, forming columns. The diffraction grating would have elongated columns and would therefore work well for each subsequent row. Therefore, the system could function for 2D operation.

VI. COMPARISON TO LITERATURE: ADVANTAGES AND DISADVANTAGES

Snapshot HSI systems that capture hypercube spectra in an instant can be achieved using creative optical designs to separate diffracted spectra in space upon an image sensor. Although these image dividing HSI systems are more common, these sacrifice resolution in one of the three measurement dimensions (i.e., X-spatial, Y-spatial, or spectral resolution). For instance, separating spectra upon a matrix image sensor entails a 1/L loss in Y-spatial resolution—where $L$ is the number of repetitions in the Y-spatial dimension being segmented for spectral separation. Ensuring the propagation of non-overlapping spectral bands onto the image sensor is important for these systems, yet difficult to achieve and requires complicated optical innovations. Conversely, multiplexed snapshot systems take the opposite approach and allow for encoded overlapping spectra to be measured by the image sensor for post-process reconstruction. Our snapshot HSI architecture system falls into this latter category and we provide a comparison of performance to the literature. A comparable multiplexed snapshot architecture, based upon using modulation and single point detection that forgoes the use of LC technology, has an acquisition time of 60 seconds [20]—compared to our snapshot HSI architecture being estimated up to 15 times faster.

It is speculated that our HSI architecture could achieve a hyperspectral acquisition 15 times faster (i.e., 4 seconds in duration) than the 60 seconds stated in the literature [20]. When the simulation was optimized for high speed operation, the simulation produced a minimum modulation time (assumed to be our best case acquisition time), $T_{\text{max}} = 4$ seconds, for a wavelength range of 400 to 800 nm and $\Delta F_j = 110$ Hz. For the parameters discussed in the previous section of this manuscript, the simulation was optimized for a larger spectral range of 250 to 950 nm, with $\Delta F_j = 90$ Hz, the maximum modulation time, $T_{\text{max}}$, was 16 seconds (and $T_{\text{max}} = 5$ seconds for a 400 to 800 nm spectral range with $\Delta F_j = 90$ Hz).

It is hypothesized that our snapshot HSI architecture could reach a hyperspectral acquisition speed of 1 second if recent advancements in LC technology, capable of 0.6 milliseconds per cycle operation [37], become commercially available and are leveraged in the snapshot HSI architecture. Additionally, we believe the snapshot HSI architecture offers further advantages, including reduced complexity and cost. This is because the snapshot HSI architecture avoids mechanical parts, and requires only a single photodiode—removing the necessity of complicated optical configurations and specialized image sensors, as are common with other snapshot HSI systems [36]. It is envisioned that as LC technology progresses, so too will the benefits of this design in the realm of snapshot hyperspectral imaging.
Spatial sampling is set by the pitch of spatial LC pixels. The minimum spatial sampling/resolution achievable is limited by undesirable diffraction effects. This can be addressed through careful selection of the pitch of the spatial pixels, $a_2$, and the pitch of the diffraction grating, $a_1$. Specifically, the pitch of the diffraction grating should be similar to the wavelength of interest, being a wavelength as large as $\lambda = 800$ nm for visible light. For example, selecting the pitch of the diffraction grating to be $a_1 = 1000$ nm may be suitable. However, the pitch of the spatial pixels should be well above the wavelength of interest to avoid undesired diffraction. A safety factor of 10 could be selected, e.g., through the inequality $a_2 \geq 10a_1$. Although this will limit the resolution of the spatial pixels, we believe it to still be suitable for most applications, as noted in the literature [38], [39]. It should also be noted that the resolution of the spatial pixels will scale with operation wavelength, so smaller resolutions are possible for ultraviolet operation.

Spatial resolution is interrelated to the number of spectral samples obtained (i.e., sampled from spatial LC pixels) in the spatial domain over a defined spectral window. The simplest way to increase spatial resolution is by decreasing the distance between the spatial LC pixels and that of the object being imaged, such that, the finest spatial feature of interest is resolved by multiple spatial samples—avoiding loss of spatial information via under sampling (i.e., Nyquist-Shannon sampling theorem [40]). The interval of spectral sampling can be estimated by dividing the spectral window of the snapshot HSI architecture by the number of spectral LC pixels. The spectral sampling interval for our snapshot HSI architecture, as determined by the experimentally-seeded simulation, is 1 nm per spectral LC pixel. Considering the spectral sampling interval, spectral resolution of this architecture is sufficient to resolve peaks with full width at half maximum (FWHM) on the order of single digit $\lambda$ ranges (i.e., 1-9 nm).

The required size of the LC shutters (i.e., LC pixels) can vary somewhat in the construction of the apparatus, if the appropriate related dimensions of the snapshot HSI architecture are adjusted accordingly. With that said, available LC spatial light modulator devices possibly adaptable for such a prototype HSI system may include, transmissive LC 2012 Spatial Light Modulator (HOLOEYE Photonics AG, Germany), SLM-S640 (JENOPTIK AG, Germany), or a transparent LC display such as LCD-057-TRN (Crystal Display Systems Ltd, United Kingdom).

The system can be discussed in terms of power consumption. Specifically, LCs can sometimes be viewed as power inefficient [41]. As such, alternative modulators are possible for eventual integration. For example, digital micro-mirror device (DMD) SLM technology is promising in terms of its power consumption. However, it should be noted that such integration may increase complexity through a reflection-based modulation rather than the transmission-based modulation of LCs [41].

The system can be discussed in terms of the alignment of the spatial light modulators. Specifically, it should be noted that such a system with two SLMs can be complicated to align. The work of Arines-Piferrer and García provides optical details on the alignment of SLMs [42].

The polarization sensitivity of the LCs can be discussed. As LCs change from transparent to opaque through the twisted-nematic (TN) effect [43], they are subject to losses of power of the image beam. Therefore, our system would be ideally suited to image intense or polarized light.

The tradeoffs between the size of the system, and the spectral resolution, and the spectral measurement window should be discussed. Specifically, when the distance between the diffraction grating and the spectral LC pixels is large (for a bulky HSI system), the spectral resolution is high and the spectral measurement window is small. Conversely, when the distance between the diffraction grating and the spectral LC pixels is small (for a compact HSI system), the spectral resolution is low and the spectral measurement window is large. These tradeoffs are further discussed in the literature [18].

It can also be noted that the LCs offer an advantage, being that they can correct for artifacts like dispersion through careful voltage control [44].

In general, alignment challenges increase with the addition of optical components. Our proposed system would have six optical components (i.e., two LC-SLM, one diffraction grating, two lenses, and one photodiode), whereas other snapshot systems have approximately 10 [20] optical components. Therefore, we believe our system to not possess extreme alignment challenges beyond what would be expected of these other systems.

Liquid crystal shutters are used to show this proof-of-concept work. However, other optical modulators could replace the liquid crystal shutters at a later time. Such other optical modulators include DMDs with fast modulation speeds [41], [45]. The increased modulation frequency of DMD based SLMs over LC based SLMs is beneficial in our Fourier based HSI architecture. Additionally, DMD-SLMs operate using a binary state modulation scheme for each pixel within the modulator, whereas, LC-SLMs are capable of multiple states (i.e., bit-depth) for each pixel during modulation [41]. The bit-depth functionality of LC-SLMs is necessary for sinusoidal modulation schemes. The proposed Fourier based HSI architecture benefits greatly from sinusoidal modulation, that is to say, the Fourier domain output of a sinusoid consists of a single peak with maximum amplitude. Conversely, the binary operation of DMD pixel modulation has non-ideal performance for our Fourier based HSI architecture, as only square wave modulation is possible. That is, the Fourier domain output of a square wave consists of many peaks, all of which are of lower amplitude.

**VII. CONCLUSION**

An exposition for a snapshot HSI architecture has been presented. The fundamental geometry, theoretical operation, and
experimental operation have been investigated in this work. The fundamental geometry of the snapshot HSI architecture deploys two transmissive LC pixel shutter arrays for mapping and acquisition of hyperspectral information using a single photodiode.

The snapshot HSI architecture’s fundamental geometry was defined using Cartesian coordinates for an incident image beam with regard to component spatial spectral beam trajectories. The fundamental geometry of the snapshot HSI architecture can be leveraged to determine the spectrum pertaining to the incident light at each spatial LC pixel position.

A framework for theoretical operation has established LSB and USB intermodulation frequency products derived from intermixing between spatial and spectral modulation frequencies. These sum and difference intermodulation frequency products have been shown to contain the information needed to map $X_{\text{image}}$ and $\lambda$ to associated $F_{\text{spatial}}$ and $F_{\text{spectral}}$ following isolation from a filter bank. This proposed framework for theoretical operation was analyzed through an experimentally-seeded simulation. Four unique spectra were frequency encoded and measured by a single detector; such that, these spectra were successfully recovered from LSB intermodulation frequency products within the Fourier-domain.

The snapshot HSI architecture’s experimental operation was shown for a principal case. The results illustrated the necessity for precise frequency placement (assuming $F_i$ and $F_j$ are on the same order of magnitude) to avoid interference between LSB and the second harmonic spectral frequencies. Optimal frequency placement should avoid integer multiples between spatial and spectral difference frequencies. Additional experimentation was performed demonstrating multiple spatial pixel operation for this snapshot HSI architecture. Two pairs of LSB and USB intermodulation frequency products (i.e., $F_{i1} \pm F_j$ and $F_{i2} \pm F_j$) were present within the Fourier-domain of the measured photodiode signal.

It is envisioned that the presented architecture can be used to establish future snapshot HSI systems based upon LC shutter technology, with $\sqrt{m} \times \sqrt{m}$ and $1 \times n$ respective spatial and spectral LC pixel shutter matrices having snapshot acquisition for mapping of hyperspectral image information using a single photodiode and Fourier-domain frequency analyses.

### APPENDIX

#### Table of Acronyms

| Acronym  | Expression                   |
|----------|------------------------------|
| HSI      | Hyperspectral Imaging        |
| CCD      | Charged Coupled Device       |
| LC       | Liquid Crystal               |
| USB      | Upper Sideband               |
| LSB      | Lower Sideband               |
| TN       | Twisted-Nematic              |
| IMS      | Image Mapping Spectrometer   |
| SLM      | Spatial Light Modulator      |
| FWHM     | Full Width at Half Maximum   |
| DMD      | Digital Micro-Mirror Device  |

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