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# **Analog spatial light modulators advances and applications**

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## **Abstract**

The performance and operation of high-speed, liquid crystal spatial light modulators are discussed in relation to a variety of system-level aspects. The issues involving the use of these devices in optical processing systems are the primary focus of this paper, but other applications such as ultra-video imaging and beamsteering are also included in the discussion.

## **1. Introduction**

Optical processors are being integrated into a variety of systems requiring high-speed signal processing. One reason for this is that the technology provides spectral processing using simple optical configurations. The processing advantage comes from the transform relationships inherent in the propagation phenomenon. As light propagates to infinity, the light's spatial distribution becomes the Fourier transform of the near-field pattern. A lens causes this transform to occur at a finite distance. To use this processing capability, it is necessary to spatially modulate a coherent light signal before it enters the Fourier transformer (i.e. the lens). The lens is capable of processing the data continuously but usable results only occur when the input data is valid. Therefore, the processing throughput of the system is limited by the ability to provide valid data to the processing elements. This is an obvious bottleneck for the processor, but it is not the only one.

Optical processing systems use two types of interface components - electrical-to-optical converters and optical-to-electrical converters which are usually spatial light modulators (SLMs) and CCD arrays, respectively. In addition to these interface devices, a variety of electronic processors are used to control or improve the optical processing results such as image processing cards to pre-process the input data and post-process the output data, SLM controllers for driving the optical processor, and a PC which acts as the user interface and controls system operation. Because of bus limitations, electronically processing or transferring large data arrays complicates system operation and lowers system throughput. The more functions that are performed electronically, the slower the system operates and the more costly the system becomes. Therefore, it is important to optimally use the processing capabilities of the optics if the system is to out perform digital systems while remaining cost competitive.

In this paper, we examine techniques for optimizing optical processing performance with regard to SLM operation. Because of various factors, the optimal performance for an SLM is a system-level issue and not limited to the specifications commonly given on the component level. Due to the complexity of this issue, we do not attempt to discuss all the various tradeoffs between different SLM technologies. Instead, we describe some system-level parameters and how these parameters relate to high frame-rate, liquid crystal on silicon (LCOS) SLMs. By using addressing structures fabricated through VLSI processes, high-speed, high-resolution optical modulators are now available. This type of SLM has proven to be a benefit to optical processing reducing the weight, size and cost of the system.

## 2. Background

In 1992, Boulder Nonlinear Systems (BNS) and the University of Colorado (CU) developed a 128x128 binary SLM system using LCOS technology.<sup>1</sup> The LCOS SLM was used to drive a ferroelectric liquid crystal modulator providing sub-millisecond frame rate operation. In that same year, BNS under contract to Martin Marietta developed a compact correlator system using the binary 128x128 FLC-SLMs. This prototype system produced good correlation results operating at over 500 fps.<sup>2</sup> In 1993, BNS and CU developed a second generation binary LCOS SLM system increasing the array size to 256x256 and improving the electronic addressing rate (load time).<sup>3</sup> The following year BNS developed an optical correlator system for Martin Marietta using these second generation SLMs. This system, which has been referenced in papers as Lockheed Martin's third generation system<sup>4</sup>, was limited by the correlation plane detector to 810 fps when using a 128x128 CCD array and to 220 fps using a 256x256 CCD array. For signal-to-noise performance, a 256x256 CCD was the optimum correlation plane detector, since it matched the space-bandwidth of the other processing components. However, it slowed the system by a factor of four. This throughput limitation was solely a function of the CCD electronics, since the optical processor had the necessary optical throughput and speed to cleanly produce sub-millisecond correlations and the correlator's drive electronics fully supported 256x256 binary operations at 1000 fps.

Because of the foreseeable limitations of strictly increasing array size, BNS ventured into a new direction. With funding from Physical Optics Corporation and NASA - Johnson Space Center, BNS teamed with CU to develop high-speed analog SLMs. The first generation SLM driver and VLSI-backplane were developed in 1994. The array size was 128x128 and an 8-bit gray-level image was loaded in 100 microseconds. These first devices were primarily used to investigate analog liquid crystal modulators.<sup>5</sup> FLC- and nematic-based modulators were investigated, but only the FLC modulators fully supported sub-millisecond gray-scale operation. In 1995, second generation drivers were developed for optical processing applications.<sup>6</sup> Under contract with the USDA, the design of an high-speed gray-scale optical correlator was started in 1996 and BNS' first prototype was completed in 1997. Also during this time, DARPA funded the design of a 4000 fps analog 512x512 LCOS SLM and the first working prototypes were fabricated in 1997.

The analog FLC-SLMs developed by BNS have virtually the same environmental characteristics and electro-optic performance as the binary FLC devices with the exception of being able to produce true gray-level modulation. That is, each frame generates a gray-level response at each

pixel unlike the temporal and spatial dithering techniques demonstrated by other researchers. Any difference in optical performance between the binary and analog devices such as efficiency or contrast is related to VLSI-backplane characteristics such as fill factor, metal quality, pixel pitch, etc. The analog FLC-SLMs are best suited for systems that require bipolar amplitude modulation such as optical wavelet processors, but their gray-scale capability is also useful for matched filter detection. Bipolar amplitude filters produce much higher signal-to-noise ratios than conventional binary phase-only filters when the input image is embedded in a cluttered background.<sup>7</sup> It is this type of capability that needs to be exploited to allow optical signal processing to become cost competitive with digital systems.

### 3. Information Processing Capacity:

As mentioned above, one of the most obvious bottlenecks is the data input rate to the optical processing elements, since the passive operation of a lens allows continuous throughput. Therefore, the efficiency of the processor is related to the throughput rate of the SLM. The amount of data supplied by an SLM is a function of frame rate, space-bandwidth product and gray-levels. The space-bandwidth product (SBP), which is directly related to the number of pixels in the array, is the parameter most often increased to improve processing efficiency. However, this parameter has the largest impact on the other system components. The SBP is directly related to the optical invariant. This relationship is

$$J_x = N_x \lambda / 4 ; J_y = N_y \lambda / 4 \text{ and } SBP = N_x N_y / 4 = 4 J_x J_y / \lambda^2 ,$$

where  $J_x$  and  $J_y$  are the optical invariants in the x and y directions and  $N_x$  and  $N_y$  are the number of resolvable samples (array elements) along the corresponding dimensions. With regard to optical performance, this means: 1) optimal processing throughput is achieved when the space-bandwidth of all system components are matched; and 2) the SBP is not limitless since a relatively large optical invariant increases the difficulty of the optical design.<sup>8</sup> In addition to the optical considerations, the SBP significantly affects all aspects of the system electronics including storage capacity, communication bandwidth and pre- and post-processing requirements. Based on these considerations, it is appropriate to assume that a larger SBP increases system costs. Therefore, the SBP is an application specific requirement, and it is best to keep it as small as possible to minimize costs.

The other two parameters (frame rate and number of gray-levels) also affect costs but not necessarily in an adverse manner. For example, less processing is required to directly use existing information than to convert it to another form such as decoding a gray-level image into bit-planes. By reducing processing functions, the system is generally simpler, faster and less costly. With regard to optical processing efficiency, the combined effect of these two parameters can be quantified using a criterion common to communication systems called channel capacity. *The channel capacity is defined as the maximum rate of reliable information transmission through a channel.* For a white band-limited Gaussian channel, the Hartley-Shannon theorem states that the channel capacity,  $C$ , is

$$C = B \log_2 (1 + S/N) \text{ bits/second/pixel}, \quad (1)$$

where  $B$  is the channel bandwidth and  $S/N$  is the mean-square signal-to-noise ratio. The Hartley-Shannon theorem is applicable to both discrete and continuous channels and is widely used in communication systems since many channels can be modeled as the Gaussian channel.

For an SLM, the channel capacity is a measure of the capability of a single pixel within the array to optically transfer information. This measure is derivable from experimental data that is commonly used to characterize SLM performance, namely response-time and contrast-ratio measurements. From SLM response curves, it is possible to find the bandwidth of the electro-optic channel using system analysis techniques, since the system response to a step function is related to its impulse response. Whereas, a contrast-ratio measurement, which is usually the average intensity difference between an on and off pixel, is related to the signal-to-noise ratio of the channel.

As an example, the response-time of one of our FLC-SLMs was measured using a fast photodetector producing the following data<sup>3</sup>:

10% to 90% rise time - ~50 microseconds;  
 $t_0$  to 10% rise - ~14 microseconds;  
 $t_0$  to 50% rise - ~35 microseconds;

where the electrical excitation signal,  $V_{in}(t)$ , at the pixel was the unit step function occurring at  $t_0$  (i.e.  $V_{in}(t) = u(t - t_0)$ ), and the output response of the photosensor was measured using an oscilloscope. From the data, an equation for the step response of the FLC channel was found to be a Gaussian function of the form:

$$V_{out}(t) = V_0 - V_0 \exp [-(t/\tau)^2],$$

where the time constant,  $\tau$ , is approximately 42.2 microseconds. It is possible to differentiate the step response to determine the impulse response and then Fourier transform the impulse response to find the bandwidth of the channel. However, it is easier in this case to first Fourier transform the step response then multiply the transform by  $j\omega$ , since the Fourier transform of a Gaussian function is well known. The channel bandwidth is found by plotting the resulting function and finding the half-power (-3 dB) points. This results in a channel bandwidth,  $B$ , for the FLC-SLM of approximately 6200 Hz.

As mentioned above, the contrast ratio is related to the channel's signal-to-noise ratio. For contrast ratio measurements, the average intensity is measured for the off and on states of the SLM. The off-state reading measures the noise power,  $N$ . For an FLC-SLM, the off-state basically produces zero-mean noise, since most of transmitted light is from small random variations in the modulator's optic-axis orientation. These variations are also spatially small usually due to subpixel structures. Therefore, much of the off-state noise is of higher spatial frequency and does not appear within the central order of the Fourier transform. This means that for many processing applications such as optical correlation most of the off-state noise is

eliminated, since the system is band-limited to spatial frequencies within the range of  $1/2d$  where  $d$  is the pixel pitch of the SLM. Within this restricted bandwidth, the off-state noise measurement is considerably smaller resulting in a larger contrast ratio usually called the zero-order contrast ratio. For the on-state, the power measurement is a combination of noise and signal (i.e.  $N + S$ ). Therefore the contrast ratio is:

$$(N + S) / N = 1 + S/N.$$

From this result and Equation 1, it is obvious that the base-2 logarithm of the contrast ratio multiplied by the channel bandwidth results in the channel capacity. For a VLSI-based SLM, the zero-order contrast ratio typically ranges from 64:1 to 128:1 (i.e. 6 to 7 bits). Therefore, the channel capacity of a VLSI-based FLC-SLM is close to 40,000 bit/second/pixel.

It is interesting to compare the channel capacity of a FLC-SLM with the actual data transfer rates of different VLSI-SLM backplanes. The following table lists the electrical performance of three different VLSI SLM systems. The values listed are actual performance (not SPICE simulations) and include any limitations imposed by the drive electronics.

SLM System (description)	Frame Rate (frames/sec)	Bits/pixel/frame	Data Rate (bits/second)	
			per pixel	per SLM
Binary 256 x 256	18,066	1	18,066	1.18 E 9
Analog 128 x 128	10,000	8	80,000	1.31 E 9
Analog 512 x 512	4,000	8	32,000	8.39 E 9

As shown in the data-rate-per-pixel column, one device actually exceeds the channel capacity. By exceeding the channel capacity, some of the data transferred at this rate is lost which means the entropy of the system is increased (i.e. the system noise increases). Therefore, the electronic data rate must be reduced to reliably convert the electronic data into a clean optical signal. Thus, the SLM electronics appear to have unusable speed. This is true if the SLM has an active drive at each pixel. However, these SLM systems use a sample-and-hold technique to store data. Data is stored by a capacitor resident at each pixel in the form of electric charge which is used to drive the LC modulator. Tests have shown that two refresh cycles are needed to fully switch the FLC modulator, since the FLC depletes the stored charge as it switches (i.e. energy is consumed in the switching process). Therefore, the high-frame rate is not used only to transfer information but to insure proper switching of the FLC modulator. This reduces the data transfer capability of the drive system by a factor of two for all of the SLMs listed in the table.

From this exercise, we find that a SLM operating at 5,000 fps with 8-bits of gray-scale optimally uses the electro-optic effect of a modulator with a Gaussian step response of 50 microseconds and 6 to 7 bits of contrast. It is unlikely that this very specific result is of much use, but this analysis uncovers a trend which is of interest from a system-level perspective. More of the capacity of an FLC channel is utilized by using a gray-level device, even though the binary

device has the highest frame rate. However, the difference in channel throughput is accentuated even more by the fact that the processing frame rate of the system is limited by factors other than the SLM's operation. A binary SLM operating at 1000 fps utilizes 1/40th of the FLC modulator capacity. Whereas, a 8-bit device at the same frame rate uses 1/5th of the capacity. For this case, the increase in processing capacity using a full-analog vs a binary channel is basically the same as using 1024x1024 vs 128x128 array. *As the system's frame rate decreases, less of the SLM's channel capacity is utilized unless the gray-scale capability of the SLM increases proportionally.*

The number of gray-levels produced by an SLM is determined by the available data. For input imagery, the data is normally produced by a "real-time" photosensor such as a CCD camera. Most real-time sensors produce analog output signals which are generally quantized by the system electronics reducing the input data per pixel to 8-bits of amplitude or less. This quantization not only increases the noise, but it also limits the dynamic range of the input sensor to approximately 6dB/bit (assuming that the sensor has more dynamic range than the system electronics). Both of these effects are undesirable. To eliminate these problems, it is possible to build continuous channels between input sensor and optical processor. This maximizes the SLM's throughput. Also, a continuous channel provides finer control of the LC modulator which is useful for optimizing its electro-optic response. The one unfortunate aspect of the continuous data channel is that it cannot be used with all SLM interfaces. The spectral data produced by the input image is typically analyzed using another SLM. This second SLM produces filter patterns from digitally stored data. The optimum number of gray-levels for this SLM is basically a cost versus performance tradeoff involving the cost of data storage and filter performance limitations due to quantized coverage of the modulator's operating curve.

System frame rate is limited by the slowest component in the data processing stream. One of the slower components is the CCD array which detects the processed results. CCD arrays require time to collect photo-induced charge, transfer the charge out of the array and convert it into output data. The optical integration time required for the CCD is a function of the optical power produced by the optical processor. However, the optical integration time is not usually a bottleneck, since there are inexpensive diode lasers that provide sufficient power. The true bottleneck is the data output rate from the CCD array. Today, there are moderate (128x128) to large arrays (512x512) which operate at approximately 1000 fps. However, array size is a substantial cost factor. Smaller arrays provide faster frame rates at less cost, but signal to noise decreases by approximately 6 dB by halving the size of the detector array. Therefore, the current limit on processor frame rate is the cost and performance constraints associated with the fast-framing CCD arrays.

#### **4. Spectral Distribution as a Function of SLM Characteristics**

As mentioned at the start of this paper, optics provides a simple method for transforming signals into spectral distributions. The accuracy of this transformation is a primary concern for most applications. Some error is introduced by the optics within the system, but the dominant errors occur in the electrical-to-optical conversion which is performed by the SLM. There are primarily three error sources: pixel width, backplane distortion and LC nonlinearity. Even though accuracy is affected, these SLM characteristics do not necessarily harm performance. For

example, it is possible to use a nonlinear LC operating curve to compress the dynamic range of a signal enhancing the range containing most of the information as is commonly done in communication systems. On the other hand, the nonlinearity produces harmonics and intermodulation products which may degrade system performance. Some knowledge of the error source is required to take advantage of its effect. Whereas, the performance of a system is adversely affected if the error sources are ignored.

One error source commonly ignored is pixel width since many SLM manufacturers are more concerned with optical efficiency. Good efficiency is crucial for many display applications, but it is also related to the pixel's fill factor which affects the spectral distribution in the Fourier domain. The pixel is basically a spatial sample point, and its width creates an envelope function in the Fourier domain. As the pixel width increases, the envelope function narrows. The exact shape of the envelope function depends on several factors such as the electric field distribution across the pixel and how the LC modulator interacts with the field as well as the shape and structure of the pixel mirror. For pixels with phase-flat mirrors several microns square, it is reasonable to assume that the SLM's modulation is a rectangular function strictly related to the pixel's fill factor,  $\tau$  (refer to Figure 1a). Then, the envelope function is a  $\sin(x)/x$  curve which produces the power spectrum shown in Figure 1b with the width of the main lobe directly related to the fill factor (i.e. width =  $2(2\pi/\tau)$ ). The sample period,  $T$ , is related to the pixel pitch as shown in Figure 1a. This spatial width corresponds to the highest spatial frequency components within an image (i.e. the  $2\pi/T$  terms shown in Figure 1b). Most optical processors block out any higher spatial frequencies, since these components arise from inter- and intra-pixel modulation and are mostly noise.

Figure 1: Pixel profiles and corresponding power spectrums in the Fourier domain.

As  $\tau$  approaches 100%, the spatial function becomes a square wave as shown in Figure 1c. For this condition, a plot of the spectral distribution (Figure 1d) shows that more light passes through the system, but the higher image frequencies are strongly attenuated by the envelope function. At the highest spatial frequency ( $2\pi/T$ ), over half of the signal power is lost (-4 dB). In most applications, this attenuation is counterproductive since preprocessing is often used to edge enhance the image. Edges are high-frequency details that characterize an object's shape, which is crucial information for pattern recognition. Also, the low-pass characteristic of the pixel envelope accentuates backplane curvature, since this phase distortion is a slowly varying function which passes through the system with greater efficiency than other spectral terms. It is possible to reduce these negative affects at the expense of optical efficiency by decreasing the fill factor which spreads the envelope function. Because of the sensitivity of the CCD arrays and the power output of laser diodes, an inefficient system still produces sufficient optical power to saturate the output detector at the maximum operating rate of the system. *In optical processing applications, a reasonable compromise is to keep the modulation flat over 25% to 50% of the pixel area.* With the smaller flat modulation area (25%), all the zero-order spectral components resulting from image data are attenuated less than 1 dB, but less than 10% of the light is in the zero-order image.

The pixel envelope is a problem in several applications, but it is not always possible to sacrifice fill factor to resolve the problem. A case being phased-array beamsteering for lidar or laser communications. In this application, the pixel envelope reduces the effective field of regard, since there is usually a minimum efficiency requirement. For an ideal phased-array beamsteerer, each array element is a monochromatic point source with no spatial extent. In this case, there is no pixel envelope and the far-field pattern is only a function of the relative phase between the waves emitted by each point source (assuming the waves have equal amplitude). If the phase increases or decreases linearly across the array, the light eventually travels in one direction which represents a single spatial frequency in the Fourier domain (i.e. far-field). Therefore, the rate at which the linear phase profile changes across the array affects the steer angle. Its steering efficiency is related to the number of array elements within a  $2\pi$  phase change, where the fixed element spacing spatially quantizes the  $2\pi$  phase shift producing noise terms and lowering the power of the main beam.

With a liquid crystal SLM, the array is illuminated with a monochromatic plane wave and the phase shift is produced by the LC modulator. As mentioned above, the optical efficiency of the SLM is related to fill factor, steering efficiency is related to the number of pixels used to produce a  $2\pi$  phase change, and the steer angle is related to the slope of the phase profile scaled by the light's wavelength (i.e. the angle is less for bluer light). These factors force the pixel pitch to be close to a wavelength with the pixel having a 100% fill factor, if efficient steering over a large field of regard is to be achieved. In addition, the phase shift produced by the LC modulator must emulate the phase profile without discontinuities which tend to occur at the  $2\pi$  to zero transition of the modulo  $2\pi$  phase ramp<sup>9</sup>. This discontinuity occurs because of cross talk between adjacent pixels. Because the pixel width is small in relation to the thickness of the LC modulator, the cross talk smoothes out the discrete pixel information which means the pixel envelope is narrowed by the interaction. Therefore, the efficiency falls off as the beam is steered to larger angles. Since the envelope function is not directly related to pixel fill factor but to electrical cross talk, the fill factor is maximized to keep efficiency as high as possible.

## 5. Time-sequential Processing

In section 3, the information throughput of the SLM is shown to be a function of the device's channel capacity which exceeds the system's processing throughput because of camera limitations. Since the camera time-integrates the processor results, time-sequential data processing using bit-plane slices of the imagery seems feasible. This allows the channel capacity of the SLM to be used to a greater extent. After all, this technique is used to produce gray-level imagery using binary SLMs. However, the problem with this approach is that there are two types of time integration: coherent and incoherent. Coherent integration requires the field's complex amplitude components to be vectorially summed together before the result is time averaged. Whereas, incoherent integration time averages the magnitudes of the separate field components. With an optical processor, the improvement in signal to noise (processing gain) is achieved through coherent integration using the spatial coherence of the signal. Because the CCD array detects intensity which is only related to the field's magnitude, the coherent integration has to occur before detection.

On the other hand, it is possible to use time slices to improve system resolution. As mentioned above, the space-bandwidth product is not limitless and affects system operation and cost. Therefore, it makes sense to find methods to synthetically increase system resolution. There are digital image reconstruction methods which generate high resolution images from several lower resolution frames using projection methods.<sup>10</sup> For this type of reconstruction method, lower-resolution images are acquired while the image sensor is in relative motion (rotational and/or translational motion) with respect to the image data (e.g. satellite imagery). The amount of motion between sequential frames is less than a pixel width. The projections onto convex sets (POCS) algorithm requires knowledge of the relative positional changes occurring between the frames. There are also optical methods for increasing the resolution of a system using the relative motion of two gratings.<sup>11,12</sup> One grating at the front of the system temporally encodes the image data, while a second grating at the output of the system decodes the data as a time-integrating detector creates the image. Another possible method based on motion is to use ultra-video displayed on a high-speed analog SLM. The ultra-video is from a moving sensor or of a moving object where the movement between frames is less than a pixel. We believe that the image created by the SLM as seen by a human has greater resolution than that of either the video frames or SLM.

As a first demonstration of the ultra-video approach, we interfaced a 128x128 a fast-framing camera running at 830 fps to our 128x128 analog FLC-SLM. The output data from the camera was 8-bits per pixel, but the data was modified by a look-up-table (LUT) to produce a linear optical response at the SLM of approximately 4-5 bits. A picture of cars in a parking lot was used as the input image. The cars were easily resolvable but their license plates were unreadable when the image on the SLM was static. We, then, added a small vibration to the camera mount and found that some of the letters on the license plate of the center car were recognizable.

These results are not too surprising, since this approach is similar to the other two techniques discussed above. In this case, however, the human brain is used to decode and analyze the

relative motion. The human brain is quite good at spatially correlating time variations occurring in two dimensional images, or else there would be more of us killed in traffic accidents. As with the POCS reconstruction, the higher resolution imagery is not just an interpolation of the lower resolution images since each frame adds new information. This new information is used to extract finer details while the repeated information helps reduce the noise through the incoherent integration process.

Further experiments need to be conducted, but this approach seems to work because:

- 1) the receptor has more spatial resolution than the display system;
- 2) the image is spatially dynamic but the variation is not greater than a pixel width per frame;
- 3) the receptor is capable of processing spatially incoherent images using time averaged data.

## 6. Conclusions

High speed analog SLMs are needed to improve the throughput and performance of optical processing systems. Many factors regarding the design and operation of the SLM affect the overall performance of a system. Therefore, performance specifications for the SLM should be based on system-level and application-specific requirements which optimize processing throughput and not on what makes a good display device.

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