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Characterization of an analog ferroelectric spatial light modulator Application to dynamic diffractive optical elements and optical information processing

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ABSTRACT

Spatial light Modulators (SLM) are key devices for the development of optical information processors. Low cost twisted nematic liquid crystal (TN-LC) SLM's are widely available and their characteristics have been extensively studied. Beside the fact that they exhibit a coupled amplitude and phase modulation, their speed is limited to approximately the video frame rate. An alternative to TN-LC devices can be the use of analog ferroelectric liquid crystal (FLC) devices. These devices now commercially available produce a gray level pure amplitude modulation at typical frame rates of 1 kHz. In order to determine its coding capabilities and its limitations, the characterization of such a device, manufactured by Boulder Nonlinear Systems Inc., is presented in this paper. This SLM has a resolution of 512 by 512 pixels with a pitch of 15 μ m and has a reflective VLSI backplane. The study of its potential applications for the display of dynamic diffractive optical elements and also as a component of an optical processor for pattern recognition will be followed by experimental results and comparisons with TN-LC devices.

Keywords: spatial light modulator, twisted nematic liquid crystal display, ferroelectric liquid crystal display, analog amplitude modulation.

1. INTRODUCTION

Optical processors are almost forty years old and the history of their development clearly shows that the Spatial Light Modulator (SLM) is their key component, but also one of their weakest components. Indeed, the poor performance and high cost of SLM's have delayed the fabrication of a practical optical processor. The principles and the architectures of optical information processing were established very early¹⁻³ and the

Optoelectronic Information Processing: Optics for Information Systems: A Critical Review, edited by P. Refregier, B. Javidi, C. Ferreira, S. Vallmitjana, Proc. of SPIE Vol. 10302 (Vol. CR81), 103020I © (2002) 2017 SPIE · CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.449680 availability of the first lasers soon contributed to the first practical developments. But due to the absence of SLM's, the input plane most often consisted of a fixed slide. In the seventies, a large number of optical processors were proposed for numerous applications⁴⁻⁷ and they all gave very promising results. But as everybody knows, almost all the proposed processors remained laboratory prototypes and never had a chance to replace electronic processors, even if at that time electronics and computers were much less powerful. There are many reasons for this; the number of applications that could benefit from the speed of an optical processor was perhaps not large enough, but the main reason was the absence of powerful, high speed, high quality and also affordable SLM's, as well for the input plane of the processor as for the filter plane. Now, the situation is changing and for several years, optical processors have been commercialized and are still available, for example from INO⁸, or BNS⁹, thanks to the availability of SLM's.

A very large number of SLM's have been investigated over the years, using almost all possible physical properties of matter to modulate light, but only few of them have survived and are now industrial products. Indeed, more than 50 types of SLM have been introduced in the past two decades¹⁰. From the beginning, SLM's have primarily been developed for large screen display.

Some of the early SLM's were based on the Pockels effect and two devices were very promising: the Phototitus optical converter with a DKDP crystal was used for large screen color display and also for optical pattern recognition, but the crystal had to work at the Curie point $(-50^{\circ}C)^{11,12}$; the Pockels Readout Optical Modulator (PROM) was used for optical processing^{13,14}, but it was limited as it required blue light for writing and red light for readout.

The first Liquid Crystal SLM's were developed in the late sixties, for example an electrically matrix addressed liquid crystal of 2x 18 elements¹⁵. Then the matrix size increased and in 1975, a 128x128 matrix addressed SLM was available¹⁶. But the most common Liquid Crystal SLM was optically addressed and developed by Hughes Corp.; it was used in optical processors for more than 10 years^{4,17,18}. Other types of SLM's were developed in the seventies, such as deformable membrane SLM's which were presented by Knight¹⁹ in a critical review of the SLM's existing in 1980. He pointed out that, due to their limitations, they had only a limited use in coherent optical processing applications.

In the last 20 years, many different SLM's have been proposed and many prototypes fabricated - for example, besides Liquid crystal SLM's, magneto-optic SLM's^{20,21}, multiple quantum wells devices (MQW)^{22,23}, Si PLZT SLM's²⁴ and Deformable Mirror Devices^{25,26}. An updated review of the state of the art of SLM's is given in a book edited by Efron²⁷ and in several special issues of 'Applied Optics' ²⁸⁻³¹.

Today, among the SLM's commercially available, mostly for display purpose, two technologies prevail: liquid crystal technology and Digital Micromirrors devices DMDTM (MEMS based technology).

This paper will focus on devices based on liquid crystal technology. The matrix electrically addressed SLM's using twisted nematic liquid crystal have progressed considerably in the last 20 years. Around 1985, the small LC TV screens were widely evaluated^{32,33}, but their poor performance (phase non-uniformity, limited resolution,...) limited their use for optical computing; then VGA, SVGA and XGA resolution SLM's were introduced in video projectors and their characteristics are now starting to meet the requirements of optical processors. During the same period, high performance optically addressed SLM's were fabricated, for example the PAL SLM from Hamamatsu³⁴.

Perhaps the most impressive progress was achieved with ferroelectric liquid crystal SLM's; high resolution Si backplane SLM's are now available^{9,35,36}.

For optical processing applications, it is important to control the amplitude and the phase modulation caused by the SLM; therefore, the characteristics of the SLM must be measured precisely. Twisted nematic liquid crystal SLM's are commonly used and their theory and experimental characterization show an amplitude and phase coupled modulation³⁷ as well as an operating speed limited to the video rate. For optical processing applications a higher data rate is required and, also in some cases, a pure phase or pure amplitude modulation is desired.

Ferroelectric liquid crystal SLM's can reach a speed of several kilohertz, but most of the devices on the market are binary bistable devices which consequently limit the applications. Although it is not so commonly known, analog amplitude only modulation is possible with specific ferroelectric SLM's; this paper presents the analysis and characterization of such a device which has only been commercialized since last year and which opens new possibilities for optical processing applications.

Section 2 describes the liquid crystal SLM's that are available today, their principle and their properties. In Section 3, the experimental characterization of an analog ferroelectric SLM is compared to the experimental characterization of a twisted nematic liquid crystal SLM. The differences of coding domains will be particularly emphasized. In Section 4, the two SLM's are used for the implemention of dynamic Diffractive Optical Elements (DOE's). The advantages of using an analog ferroelectric SLM in an optical correlator are analyzed in Section 5. The last section includes a summary and conclusions.

2. LIQUID CRYSTAL SLM's

2.1. Liquid crystal SLM's

Most commercially available SLM's are liquid crystal devices, except Digital Micromirrors Devices $(DMD^{TM})^{38}$ that are commercialized by Texas Instruments. The liquid crystals show intermediate physical properties between liquids and solids³⁹. They have a liquid aspect but present a structured molecular arrangement. There are different phases of liquid crystals depending on the molecules arrangement type, as shown in Figure 1. The nematic phase has orientational order and no positional order and the smectic phase has orientational order and positional order only in one dimension and is formed in a layered structure. These layers can slide over one another like soap. The star added to the name of the phase indicates that the structure is chiral (twisted nematic N*, smectic C*...).

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Figure 1: Various phases of liquid crystal, N: nematic, Sm A: Smectic A, Sm C: Smectic C, N*: twisted nematic.

2.1.1. Nematic Liquid crystal

In a twisted nematic liquid crystal $(TN-LC)^{39}$ cell, the liquid crystal molecules are arranged in the form of a helix. The increase in the voltage applied to the cell changes the regularity of the twist. Therefore, the birefringence is modified, leading to polarization and phase modulation. A polarizer placed at the output of the TN-LC SLM allows intensity modulation. According to the polarization direction of the beam illuminating the SLM and to the orientation of the output polarizer, different operating modes of the SLM are possible. These modes range from a near pure phase modulation mode to a near pure amplitude modulation mode. All liquid crystals require a DC balanced drive signal in order to prevent the destruction of the liquid crystals and therefore the signal must be followed by its inverse. Since nematic liquid crystals are only sensitive to the rms average value of the applied voltage, the inverse signal will not affect the optical output of the SLM. Nematic devices have fast optical rise times (about 50-1000 µs) but slow fall times (several ms); therefore the operating speed of TN-LC SLM's is mostly limited to the video rate.

For another type of nematic liquid crystals, the molecules are aligned parallel in a parallel aligned device (PAL-LCD)³⁴. Such a cell behaves as a tunable retardation plate. Optically addressed PAL SLM's are commercialized by Hamamatsu and a pure dephasing of 2π is possible.

2.1.2. Ferroelectric liquid crystal

Ferroelectric liquid crystals have been studied extensively as shown by Patel *et al.*⁴⁰ and Moddel⁴¹ in a book dedicated to SLM's²⁷. The literature on smectic liquid crystals reveals an incredibly large variety of devices providing different possibilities of modulation, as described by de Bougrenet *et al.*⁴².

Most smectic phases are smectic A and smectic C phases (see Figure 1). The chiral smectic C or smectic C* phase, shown in Figure 2, is commonly used in SLM's. Smectic C* liquid crystals are ferroelectric liquid crystals (FLC's).



Figure 2: Structure of the smectic C^* phase (after⁴⁰).

The properties of a smectic C* device, in terms of behavior and modulation capability, depend greatly on different factors such as the liquid crystal itself (chemical contents, helix pitch,...), or on the device parameters (cell thickness, alignment of the molecule, FLC layer structure,...) or on the electronic driver. Therefore, since the end user of an SLM has no access to all the SLM physical parameters, he will have difficulties in analyzing some characteristics and constructing a precise physical model of the SLM.

Currently in most SLM's using smectic C*, the liquid crystal presents a bistable electrooptic effect which can give a binary phase or binary amplitude modulation. Smectic C* devices have a fast optical rise and fall time (about 10μ s - 200μ s).

Gray level modulation (intensity or phase) is possible indirectly with binary FLC, by spatial or temporal averaging⁴¹. Temporal averaging in used for video display but cannot be used for optical processing applications. Distorted helix ferroelectric liquid crystal (DHFLC) also allows gray level modulation⁴¹.

Smectic C* can also be used for building analog/multilevel SLM's⁴³⁻⁴⁷ and the ferroelectric device presented here enters this category. This device modulates the light similarly to a passive half-wave retarder and the applied electric field results in a rotation of the half-wave retarder slow axis about the optic axis. That is why a pure amplitude modulation can be obtained.

FLC's have an electrical polarization even in the absence of an externally applied electric field. Therefore, the molecules respond directly to an applied field and to its polarity. As for nematic liquid crystals, in order to maintain the DC balance required to avoid the destruction of the liquid crystal, every frame written must be followed by its inverse. But for FLC's, due to their sensitivity to polarity, this results in an "inverse" image displayed by the SLM. If this image cannot be used, the operating frame rate is then divided by two and the output detected must be triggered by a signal from the electronic driver of the SLM.

2.2. SLM's characteristics

Ideally, the characteristics of an SLM should fulfill the requirements of the application. But in reality, as shown by the different processors developed until today, the ideal SLM does not exist and researchers tried to use available SLM's even if they were not well suited. It should also be noted that most of the commercially available SLM's are designed primarily for display applications that have not the same requirements as optical computing applications. The principal characteristics listed here are valid for all types of SLM's and not only Liquid Crystal SLM's. They are useful for the comparison of the different SLM's.

2.2.1 Addressing

SLM's can be classified into two categories, the ones addressed optically (OASLM) and the ones addressed electrically (EASLM). In the case of an OASLM, there is an optical write beam that controls the modulation of the read beam. The write beam can be coherent or incoherent. An EASLM consists of an electrical-optical interface and the optical output signal is pixilated. There are two types of EASLM's. The EASLM can be matrix addressed; in this case, the SLM works in a transmission mode and consists of a layer of liquid crystal between two glass plates. Crossed electrodes are deposited on each plate and thin film transistors (TFT) can be added to increase the addressing speed.

The EASLM can also be a reflective device; in this case, the liquid crystal lies between an active backplane and a glass plate with transparent electrodes. The most common active backplane is a Si backplane and therefore, the VLSI technology is used for the driving circuitry and smart pixels can be built. The light to be modulated is reflected by the Si backplane surface through the liquid crystal. The advantages of active backplane SLM's are numerous: higher addressing speed, better light efficiency, smaller dead zones. Therefore, for high speed SLM's used in optical processors, active backplane SLM's are best suited. But their fabrication is delicate, since the backplane must be planarized during the foundry process.

The two SLM's presented in this paper are EASLM's-one matrix addressed, the other with a Si backplane.

2.2.2. Resolution

The resolution of the various SLM's is now approximately the same, but continuously increases with technological progress. OASLM's have a higher resolution compared with EASLM's. Commercially available twisted nematic liquid crystal SLM's and Digital Micromirror Devices (DMDTM)³⁸ exhibit XGA or higher resolutions; most of the ferroelectric liquid crystal SLM's have a lower resolution (512x512), but XGA resolution is also obtained³⁵.

2.2.3. Pixel size, pixel pitch, fill factor

Due to the addressing electronics, not all the surface of an SLM is active. The fill factor gives the amount of light that is really modulated by the SLM. A high fill factor will therefore increase the light efficiency of the SLM and fill factors of 90% are now possible with reflective SLM's. A small pixel pitch is interesting for optical processors, since it increases their compactness. SLM's with a pixel pitch of $7\mu m$ are now available⁴⁸.

2.2.4. Contrast ratio

Most of the time, it is defined as the ratio between the maximum intensity and the minimum intensity transmitted or reflected according to the type of SLM. For some SLM's, especially for display applications, the contrast ratio can be manually adjusted

via the driving electronics. For optical processors, the contrast should be the highest possible in order to reduce noise.

2.2.5. Operating rate

The operating rate depends on the material used in the SLM and on the driving electronics. Some materials, such as twisted nematic liquid crystal, are relatively slow and operate at video rate. Ferroelectric liquid crystal and micromirrors SLM's are faster (tens of kiloHertz). The problem is to fabricate electronic drivers capable of reaching these rates. For display applications, the SLM driver input signal works at video rate, and the high speed of the SLM then allows gray levels and color by temporal multiplexing^{35,36}. Most of the time, the end user has no possibilities to drive the SLM sold for display applications at higher speed. For optical computing, the advantage of optics in terms of speed disappears if the input data are entered at the video rate. Therefore, one of the challenges today is to build electronic drivers that can match the potential speed of the SLM.

2.2.6. Coding domains

All the above SLM parameters are important for both applications, display and optical processing. But the coding domain of a SLM which represents the range of complex values that can be reproduced, is particularly crucial for optical processing applications. Indeed, for display, only the intensity modulation is important, not the phase. Ideally, it would be interesting to code values in the full complex plane. But in fact, the possible values are limited. Since SLM's are passive devices that can only attenuate the beam which is passing through, the values will already be limited to the unity circle (Figure 3a). Unfortunately, no existing SLM's can address the whole unity circle; some are amplitude only modulators (Figure 3b), some phase only modulators (Figure 3c) and in many cases, the amplitude and the phase are coupled (Figure 3i).



Figure 3: Examples of coding domains: (a) unity disk, (b) pure amplitude, (c) pure phase, (d) amplitude only, (e) pure binary phase, (f) ternary phase, (g) quantified amplitude only, (h) quantified phase only, (i) 2π spiral.

Table 1 presents a summary of the coding domains produced by liquid crystals. It can be noted that the TN-LC offers the largest range of coding domains, even if the pure amplitude modulation is only partially reached; and, as shown in the next Section, all these domains can be reached at least partially with the same TN-LC SLM by changing the orientation of the polarizers. In the case of FLC SLM's, some coding domains can only be reached by a specific FLC SLM: for example, pure analog amplitude modulation cannot be obtained with a binary bistable FLC SLM.

For optical processing applications, many authors have shown that phase only modulation is very interesting for filters and DOE's if the maximum phase shift obtained by the SLM reaches 2π . As shown in Table 1, this is possible with PAL LC SLM's and TN-LC SLM's. But it should be noted that commercially available TN-LC SLM's for display now reach a phase shift which is smaller than 2π ; due to fabrication specifications, they are thinner than they used to be.

Type of LC	LC retardation	coding domain
PAL-LC	0-2π	
TN-LC	0-2π	
FLC	π	
Analog FLC	π	LT R

Table 1: Summary of the coding domains of the different SLM's using liquid crystal.

An analog ferroelectric SLM is characterized in the next section. With this type of SLM that works as a half wave plate, different coding domains can be obtained, as will be demonstrated here by computing the two orthogonal polarized light components using the Jones matrix.

For each cell, the orientation of the optical axis can be adjusted from $-\pi/8$ to $+\pi/8$. By adding a half-wave plate (see Figure 4), as suggested by Bauchert *et al.*⁴⁹, the user can tune the range of amplitude modulation attainable, as shown in Table 2.



Figure 4: Optical setup for producing pure amplitude coding domains. PBS stands for polarizing beam splitter. $t_{xx} E_0$ and $t_{xy} E_0$ represent the two projections of E_0 onto orthogonal polarization directions.



 Table 2: Coding domains attainable when adding a half wave plate into the optical setup. The coding domain can be chosen by rotating the half wave plate.

Adding an extra quarter-wave plate (see Figure 5) to the half-wave plate can greatly extend the modulation capabilities of an analog FLC SLM: both a pure phase-only modulation (over $\pi/2$), - as with PAL LC -, is attainable (according to Bauchert *et al.*⁴⁹), and a coupled phase-amplitude modulation, - as with TN-LC - can be obtained. These capabilities are summarized in Table 3.



Figure 5: Optical setup for producing phase and amplitude coding domains (according to Bauchert et al.⁴⁹).



Table 3: Coding domains attainable when adding a half wave plate and a quarter wave plate into the optical setup. The coding domain can be chosen by rotating the two plates (after Bauchert *et al.*⁴⁹).

3. CHARACTERIZATION

The characterization of an SLM is particularly important when it is used for optical information processing applications. The SLM transfer function, both in its amplitude and in its phase, must then be known precisely. For example, an SLM implementing a dynamic DOE must transform an incoming wavefront into another wavefront with the desired amplitude and phase. Or, when the SLM is used as an input device or filter in an optical processor, the phase and the amplitude of the signal have a great influence, especially if the processor is coherent. In order to compare their performance, the experimental characteristics of a twisted nematic liquid SLM from CRL³⁵ will be measured, then followed by the experimental characterization of an analog ferroelectric SLM from BNS⁹.

3.1. Characterization of a TN-LC SLM

The characterization methods for SLM have been extensively studied, as shown in a short review given in reference ⁵⁰. They are mainly applied to TN-LC SLM's. The SLM to be characterized must be placed between a polarizer/analyzer pair. (see Figure 6)



Figure 6: Optical system used for the characterization of the SLM. P and A are respectively the polarizer and the analyzer.

The device characterization is performed through the determination of Jones matrices⁵¹⁻⁵⁴: this technique provides an empirical model for the LC matrix and then allows the user to predict the device behavior for given configurations of the polarizer and analyzer. Historically, this characterization was performed using a Mach-Zehnder interferometer, but the data obtained for the phase measurement were often noisy and hard to exploit⁵⁵, as could be verified.

Thus, for a given modulating cell (i.e. a pixel) sandwiched between an analyzer and a polarizer with the respective azimuth angles ψ_a and ψ_b , the output Jones vector is calculated to be⁵²:

$$\begin{pmatrix} x_{out} \\ y_{out} \end{pmatrix} = P(\psi_A) . J . P(\psi_P) . \begin{pmatrix} x_{in} \\ y_{in} \end{pmatrix}$$
(1)

if $\begin{pmatrix} x_{in} \\ y_{in} \end{pmatrix}$ denotes the incident Jones vector, J the Jones matrix of the LC cell and $P(\psi)$ the

Jones matrix of a polarizer azimuth angle ψ . *J* is described by:

$$J = c. \exp[-i\beta] \begin{pmatrix} f - ig & -h - ij \\ h - ij & f + ig \end{pmatrix}$$
(2)

where c represents intensity loss by surface reflections, etc, β represents the birefringence, i represents the imaginary unit and $P(\psi)$ is expressed as:

$$P(\psi) = \begin{pmatrix} \cos^2 \psi & \sin \psi \cos \psi \\ \sin \psi \cos \psi & \sin^2 \psi \end{pmatrix}$$
(3)

To fully characterize the modulator, its Jones matrix J (actually one per gray level) must be determined. To do so, the technique used in this paper, as suggested by Colin⁵³, first consists in measuring, for gray level values ranging from 0 to 255 (here, an increment of 10 levels gives a total of 27 gray levels), the amplitude transmittance of the SLM using six different polarizer/analyzer configurations listed in Table 4. Each of them gives a particular equation of the transmittance. The measurements were performed at a wavelength of 633 nm.

The first series of intensity measurements concerns the central order of the diffraction pattern due to the SLM electrode grid when a uniform gray level image is displayed.

Configuration	ψ_{P}	ψ_{A}	Intensity
1	0	0	$c^2(f^2+g^2)$
2	0	π/4	$c^2(0.5+fh+gj)$
3	0	π/2	$c^2(h^2+j^2)$
4	π/4	-π/4	$c^2(h^2+g^2)$
5	π/4	0	$c^2(0.5-fh+gj)$
6	π/4	π/4	$c^2(f^2+j^2)$

Table 4:Equation system used for amplitude measurements (after Colin⁵³) when a gray-level pattern is displayed on the SLM.

For each gray level, the solution of the six-equation system of Table 4 corresponding to these amplitude measurements gives the absolute value of f,g,h,j and the products fh and

gj. To determine the entire Jones matrix, i.e. the signs of f,g,h, and j, additional experiments for each gray level are necessary. So, a Ronchi ruling⁵¹ (a binary grating with a 50% duty cycle) is displayed on the SLM to measure the intensity of the central order and of the 1/2 order (supplementary diffraction order due to the Ronchi grating only and not to the SLM electrode grid) of its diffraction pattern, for the six configurations listed in Table 5.

Configuration	ψ_{P}	$\psi_{\scriptscriptstyle A}$	Dephasing $\phi_2 - \phi_1$
1	0	0	$\beta + \arctan(g/f)$
2	0	π/4	$\beta + \arctan[(g+j)/(f+h)]$
3	0	π/2	$\beta + \arctan(j/h)$
4	π/4	$-\pi/4$	$\beta + \arctan(g/-h)$
5	π/4	0	$\beta + \arctan[(g+j)/(f-h)]$
6	π/4	π/4	$\beta + \arctan(j/f)$

Table 5: Expression of the phase retardation for the six considered configurations (after reference⁵³) when a Ronchi ruling is displayed on the SLM.

From these measured intensities, the dephasing between the two gray levels of the grating can be computed. Equation 4 shows the expression of the intensity of the $\left(\frac{p}{2}\right)^{th}$ diffraction order, with m_1 and m_2 the intensities of the corresponding zero order when the two spectrum hands are disclosed in the spectrum of th

the two gray levels are displayed independently, as in the previous series of measurements. $\phi_2 - \phi_1$ is the dephasing between the two gray levels, N the number of columns of the grating and a the width of each column (i.e. the modulator pitch).

$$\left|A(\frac{p}{2},0)\right|^{2} = \frac{N^{2}}{4}a^{2}.\operatorname{sinc}^{2}(\frac{a.p}{2b}).\left[m_{1}^{2} + m_{2}^{2} + 2m_{1}m_{2}\cos(\phi_{1} - \phi_{2})\right]$$
(4)

where b is the grating total width. For better accuracy, redundant measurements are performed for p=0 and p=1.

The dephasing values $\phi_2 - \phi_1$ that are obtained from Equation 4 can then be input in the six-equation system described in Table 5 and finally, the signs of f, g, h, j can be determined.

3.2. Experimental characterization of a TN-LC SLM

The experimental characterization of the SVGA 1 SLM from CRL Opto is presented here. It is a Polysilicon TFT twisted nematic Liquid Crystal Display (LCD) and the device specifications are given in Table 6.

This SLM is designed to be directly driven by a SVGA video signal delivered by a computer. Such devices cannot operate at frame rates higher than a few tens of Hertz because of the low commutation speed of twisted nematic liquid crystal molecules.

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Parameters	Specifications		
Size	33 mm diagonal		
Resolution	800 x 600		
Pixel size	26 (H) x 24 (V) μm		
Pixel pitch	33 x 33 μm		
Fill factor	57 %		
Transmission	typically 11 %		
Contrast Ratio	200:1		
Electro-optic response	t-on 7ms, t-off 25 ms @ 25 °C		
Modulation	continuous grayscale		
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Table 6: Part of the SVGA 1 SLM data sheet after CRL³⁵.

The six polarizer/analyzer configurations used in the experiments give very different behaviors of the device. Figure 7 shows the curves obtained for the six configurations used during the characterization. At 633 nm, maximum dephasing was $3\pi/2$, which is lower than the ones obtained with the previous generation of devices which were thicker. Labastida *et al.*⁵⁶ reported such a behavior with a similar device.



Figure 7: Six coding domains resulting from the characterization at 633 nm of the CRL SVGA1 TN SLM, corresponding to six polarizer/analyser configurations.

Using the Jones model, it is possible to select the experimental domain that is close to the requirements imposed by the application using the SLM. Three selected experimental domains which are close to their equivalent theoretical ones are presented in Figure 8. The $(20^\circ, 80^\circ)$ domain corresponds to a phase-mostly mode with maximum dephasing of $3\pi/2$. With this SLM, an amplitude-mostly mode is difficult to reach. For a $(20^\circ, -90^\circ)$ configuration, a strong coupling between phase and amplitude is obtained. The $(45^\circ, 45^\circ)$ configuration corresponds to a phase-mostly mode with maximum dephasing of π . After this characterization, the model of the SLM can be used for the choice of the coding domains suitable for the desired application.



Figure 8: Selected experimental domains at 633nm available for the CRL SVGA1 TN SLM.

3.3. Characterization of an analog ferroelectric liquid crystal SLM

3.3.1. SLM specifications

This is the experimental characterization of an analog ferroelectric liquid crystal from Boulder Nonlinear Systems. BNS gives the following specifications for this SLM:

Parameters	Specifications	
Array size	7.68 x 7.68 mm	
Resolution	512 x 512	
Pixel pitch	15 μm	
Fill factor	83 %	
Contrast ratio	200:1 (zero order monochromatic light)	
Modulation uniformity	$\lambda/4$ or better	
Liquid crystal	Smectic C* FLC	
Optical modulation	variable polarization rotation	
Device configuration	reflective	
Optical response (10%-90%)	50-150µs	
Full frame loading	≤ 165µs	
Maximun usable frame	1017 Hz	
Electrical addressing	32 8 bit DACs	
Driver memory	1024 frames of SDRAM	
Driver interfaces	ISA bus or PCI bus computer slot	
	32 bit high-speed data port loads full	
	frame in 165 µs, laser modulation	
	signal, detector synchronization signal	

Table 7: Part of the 512x512 analog ferroelectric SLM data sheet after BNS⁹.

The same device can be filled with nematic liquid crystal instead of Smectic C* FLC. This SLM has been commercialized by BNS since 2000 and there is another version of this analog 512x512 SLM that features a pixel pitch of 7 μ m and has been developed for correlation applications.

Since the Smectic C* SLM acts typically as a passive half-wave retarder, it has to be fabricated for a specific wavelength. The use of another wavelength than the specified one results in a loss of optical efficiency.

The specifications of the electronic driver are related to the new driver that we have not tested yet, since it was not available when this work was completed. Therefore, it is important to note that for all the experiments presented in this paper a prototype driver was used. The prototype driver has only limited performance; it supports only two frames of storage of 4 bits per pixel. The new driver supports 8 bits per pixel that are mapped through a Look-Up-Table (LUT) to linearize the optical response of the SLM, as the liquid crystal does not respond linearly to voltage applied⁴⁸ as shown in the next subsection. Figure 9 shows the SLM circuit.



Figure 9: The 512x512 multi-level SLM (photo courtesy Kipp Bauchert BNS).

The fabrication of this device is described in a paper by Bauchert *et al.* from BNS⁴⁸. Since the Si Backplane acts as a mirror, its planarity will determine the quality of the SLM. Therefore, the fabrication process has a feature size of 0.5 μ m. It utilizes planarization after each step of the foundry process and it has an additional metal layer and uses a "shiny" metal technique for the final layer. The quality of planarization is shown in Figure 10 with a microscope image of a few pixels.



Figure 10: Microscope image of a few pixels of the 512x512 multi-level SLM (photo courtesy Kipp Bauchert, BNS).

According to BNS⁴⁸, the efficiency measured in the zero-order diffraction spot is approximately 65% of the measured efficiency for a flat mirror. This loss includes loss due to the fill-factor, absorption, and loss due to higher frequency diffraction. For this measurement no cover glass and no liquid crystal were present.

3.3.2. The analog SLM as a display

It must be remembered that, the prototype driver was used for all the measurements; so, there is no linearization of the amplitude response of the SLM. In order to avoid damaging the SLM, the Sm C* liquid crystal needs to be DC balanced. To meet these requirements a "true" image and then an "inverse" image must be written in succession. Therefore, the frame rate is divided by a factor two, and the detection of the processor output must be synchronized to eliminate the unwanted results. Figure 11 shows the direct and the inverse image of the same test pattern from BNS displayed on the SLM.



Figure 11: Test pattern provided by BNS displayed on the analog SLM controlled by the prototype driver (a) Direct image (b) inverse image, the edges of the picture represent the SLM non-controllable zone.

The 512*512 grid displayed on the SLM (see Figure 12) shows the quality of the display in terms of resolution and contrast ratio.



Figure 12 : Grid displayed on the analog SLM (the edges of the picture represent the SLM noncontrollable zone).

3.3.3. Amplitude and phase characterization

In a similar experiment to the one for TN-LC SLM's, the 16 gray levels were displayed uniformly on the SLM, and the intensity in the 0th order of the diffraction due to the SLM was recorder for each level. The resulting curve, intensity versus gray levels has the same shape as the curve of Figure 13. The ratio between the intensity corresponding to the highest gray level and lowest gray level was approximately 160, in agreement with the value of the contrast ratio of the SLM specification.



Intensity response

Figure 13: Intensity response of the analog FLC SLM.

The liquid crystal does not respond linearily to the applied voltage⁴⁸. Since the prototype driver which is used here sends directly the voltage corresponding to the gray level with no linearization correction, it is possible to measure the response of the FLC to the voltage.

The second experiment similar to the one with the TN-LC SLM described in the previous section was carried out. 16 gratings, each one with a different gray level, were displayed successively on the SLM; the intensity of the 0^{th} order and 1^{st} diffraction order due to the grating were measured and are recorded in Figure 14.

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0th and 1st diffraction orders of the grating



Figure 14: Intensity of the 0th order and of the 1st diffraction order when a grating with variable gray levels is displayed on the SLM.

Figure 14 clearly shows the non-linear behavior of the liquid crystal; it also shows thatwhere possible- an input voltage can be found to linearize the output.

If the ratio between the 1st order and the 0th order is constant, the dephasing of the SLM is also constant. As represented in Figure 15, the dephasing of the SLM is constant except for low values of the input. A similar behavior has been described by Abdulahim⁵⁷. The dephasing was not measured, since with the final electronic driver, dephasing should be constant and the SLM should work as a pure amplitude modulator.



Figure 15: Ratio between the intensity of the 0th order and the 1st diffraction order.

4. DYNAMIC DOE's

The fixed Diffractive Optical Elements (DOE's) are now commonly used thanks to the progress in the algorithms and of the fabrication techniques. However, in order to add flexibility to the optical processors, the DOE's should be dynamic and have a fast response time. A dynamic DOE must be displayed onto a SLM and, as seen before, the SLM's are now better suited to the DOE's requirements in terms of coding domains and resolution. Applications of dynamic DOE's include programmable lenses, reconfigurable optical interconnects, dynamic display, structured light projection, reconfigurable filters⁵⁰.... With a SLM giving continuous phase modulation between 0 and 2 π , DOE's with high diffraction efficiency and high SNR reconstruction can be implemented. This dephasing is obtained with nematic liquid crystal SLM's, such as PAL SLM's. As seen in the previous section, a TN-LC SLM merely approaches the pure phase modulation and current SLM's dephasing is lower than 2 π . Moreover, these SLM's have a data rate limited to approximately 60 Hz. To increase this data rate, the use of FLC SLM's is a solution; however, most of the current devices are amplitude or phase bipolar, except the analog SLM described in the previous section. The computation and the simulation of DOE's clearly demonstrate, that in terms of reconstruction quality measured by the SNR, multiple amplitude level encoding of the DOE is largely superior to binary phase encoding. This is illustrated by Figure 16. The input image size is 128x128 pixels, the DOE size is 512x512 pixels. The DOE is duplicated 4 times in each direction in order to reduce the speckle effect, which gives the pixilated aspect to the reconstruction. The DOE was computed using the IFTA algorithm⁵⁸. In order to compare their encoding performance, two DOE's were computed - one with binary phase encoding, a second with a 8-amplitude level encoding. Their reconstructions are given respectively in Figure 16 a and Figure 16 b.



Figure 16: Simulation of the reconstruction of a DOE computed with different encodings; (a) binary phase, (b) 8 amplitude levels.

DOE encoding	Diffraction efficiency	SNR in amplitude
binary phase	40.81 %	13.3
8 amplitude levels	5.49 %	467

Table 8: Characteristics of simulations presented Figure 16.

Table 8 clearly shows that if the quality of the reconstruction is more important than the diffraction efficiency, the pure amplitude encoding should be used instead of the binary phase encoding and therefore, the analog FLC SLM should be preferred to the binary FLC SLM.

4.1. Dynamic DOE's on a TN-LC SLM

To compare the use of the TN-LC SLM and the analog FLC SLM for dynamic DOE's implementation, the 8-amplitude-level-encoded DOE shown previously, was displayed on the SVGA 1 SLM. The polarizer/analyzer combination was $(0^{\circ},90^{\circ})$ (see Figure 7). The reconstruction of Figure 17 a, shows that there is no pure amplitude modulation but that the coupled phase modulation degrades the quality of the reconstruction considerably. It is also possible to compute a DOE with an amplitude/phase coupled modulation taking account of one experimental coding domain of the SLM. This is the case of the reconstruction presented Figure 17b, where the phase mostly mode corresponding to the $(20^{\circ},80^{\circ})$ polarizer/analyzer configuration (see Figure 8) was used. The reconstruction is improved and the complex conjugate is weak.



Figure 17: Optical reconstruction of the DOE displayed on the TN-SLM SGA1 (a) DOE encoded on 8 amplitude levels, SLM polarizer/analyser configuration (0°,90°), (b) DOE encoded on 8 amplitude/phase coupled levels, SLM polarizer/analyser configuration (20°,80°).

4.2. Dynamic DOE on an analog ferroelectric SLM

The same DOE coded on 8 amplitude levels was displayed on the 512x512 analog FLC SLM using the prototype electronic driver. The reconstruction quality clearly appears in Figure 18. However, because the prototype driver does not linearize the SLM response, the gray levels are not accurately reproduced. Therefore, the reconstruction of the binary amplitude encoded DOE displayed in Figure 19, shows no clear quality decrease compared to 8 amplitude level encoded DOE.



Figure 18: Optical reconstruction of a DOE encoded on 8 amplitude levels and displayed on the analog FLC SLM, (a) reconstruction plane, (b) zoom with one first order reconstruction.



Figure 19: Optical reconstruction of a DOE with binary amplitude encoding, displayed on the analog FLC SLM, (a) reconstruction plane, (b) zoom with one first order reconstruction.

The quality of the reconstruction in Figure 20, representing a logo with a gray scale, demonstrates the potential of the 512x512 analog FLC SLM for implementing dynamic DOE's. The new electronic driver which linearizes the SLM behavior should give excellent results.



Figure 20: Optical reconstruction of a DOE encoded on 8 amplitude levels and displayed on the analog FLC SLM.

5. OPTICAL PROCESSOR

In Fourier optics, phase-only modulation has always been very popular since no attenuation of the signal energy is performed⁵⁹. Nevertheless, the benefit of pure-amplitude modulation over other types of modulation has already been established in some cases^{60,61} for optical correlation. They will be reviewed in the following part. In any case, if the exact value of the correlation function is needed (for further computation, as in⁶²), any distortion should be avoided and then real-valued images must be displayed as real-valued distributions with a pure-amplitude SLM.

5.1. 4f correlator case

The input image is displayed in the space direct domain and is therefore real-valued. It can therefore seem natural that the most accurate implementation of this image is onto a pure-amplitude domain as verified by Mazé and Réfrégier in ref^{60} .

As far as the filter is concerned it is implemented in the Fourier domain and exhibits values distributed in the whole complex plane. As established by Laude and Réfrégier⁶³ and Juday ("Coupling is your friend")⁶⁴, the use of a pure amplitude modulation is not the best solution in this case and a coupled phase-amplitude modulation should be preferred. If the use of the pure-amplitude modulation is the only available solution (i.e. if the only available SLM is a smectic C* SLM for instance), cell-oriented techniques, though very popular, should be avoided and replaced with a point-oriented Euclidean projection^{63,65,66}, proved to be more adapted⁶⁶ (and even optimal).

5.2. Joint Transform Correlator (JTC) case

In the JTC case, since the input image is displayed in the space domain, as in the 4f case, the conclusions are exactly the same as above with the 4f correlator as far as the input image is concerned.

But contrary to the 4f case, the correlation filter is not displayed in the Fourier domain; its impulse response is displayed (i.e. the reference object), which is real valued, even if any matched filter, an inverse filter, a combination of them (OT filter⁶⁷ or MINACE filter⁶⁸) or a synthetic discriminant function filter⁶⁹ is chosen instead of the classic reference. Therefore, a pure-amplitude implementation should be preferred, as demonstrated by Bigué and Ambs⁶¹. If only a coupled SLM is available, only values on the real axis (or close to it) should be used.

Even if, seemingly, no theoretical study has been carried out to determine which coding domain should be preferred for the display of the Joint Power Spectrum (JPS), binary coding, possible with any modulator, has been used in most works since Javidi's pioneering papers (see for instance B. Javidi and C.-J. Kuo⁷⁰). Many binarization techniques have been proposed to produce a non linearity in the joint power spectrum plane. These non-linearities can enhance several capabilities of the correlator, as demonstrated by Réfrégier *et al.*⁷¹ and therefore have an influence on the results in the correlation plane.

5.3. Simulations

A few simulations show that the classic use of TN-LC SLM's instead of perfect gray scale modulators for the display of gray level images in optical correlators can produce huge errors. With analog C* FLC SLM's, the problem disappears since the SLM is supposed to produce a pure amplitude modulation. A pure analog modulator is compared with a TN-LC SLM producing a coupled phase-amplitude modulation with maximum dephasing of 2π .

5.3.1. 4f correlator case

Only the display of the input image is taken into account. In this case, for clarity reasons, the filter, in the Fourier plane, is supposed to be perfectly displayed. Since an autocorrelation is computed, it is only the Fourier transform of the input image. The gray level pattern depicted Figure 21 (a pyramid) is chosen as the input image. Using a TN-LC SLM instead of a true amplitude modulator clearly modifies the correlation function, as shown in Figure 21



a) b) c) Figure 21: (a) input image, (b) 4f correlation function when using an FLC SLM, (c) 4f correlation function when using a TN-LC SLM.

5.3.2. Joint Transform Correlator case

In this case, the displays of the input image, of the « filter » (actually, the reference image in the space domain) and of the joint power spectrum are taken into account. The same test pattern as in the previous subsection was used and the arrangment of the input plane is described in Figure 22a. Using a TN-LC SLM in both the input and joint power spectrum planes clearly leads to a false solution: additional orders appear and the expected crosscorrelation orders are not correct.



Figure 22: (a) JTC input plane, (b) Joint Power Spectrum and (d) JTC correlation function when using an FLC SLM, (c) Joint Power Spectrum and (e) JTC correlation function when using a TN-LC SLM. The interesting part of the correlation plane consists of the two crosscorrelation orders at the top and the bottom of the plane (as in Figure d). The additional orders in Figure e are parasitic.

6. CONCLUSIONS

The availability of a multilevel amplitude FLC SLM now opens new opportunities for optical information processing applications. A short historical review of the evolution of SLM's in the 30 last years has shown their importance for the optical processing

development, and also their rapid progress in the last decade. Indeed, today's commercially available SLM's are mostly for display purpose. Moreover, their characteristics are now approaching the requirements of optical information processors in terms of speed, optical quality and resolution. Two of these SLM's have been presented here; one TN-LS SLM with a SVGA resolution which is now commonly used by many researchers, and a 512x512 multilevel analog SLM from BNS which has only been commercialized since last year. Contrary to most FLC SLM's which produce a binary amplitude or phase modulation, this SLM produces a pure multilevel amplitude modulation. Therefore, this SLM has a double advantage over the TN-SLM, the speed advantage as for all FLC SLM's and the fact that there is no phase coupled with the amplitude modulation. This later advantage has been demonstrated by the experimental study of both SLM's coding domains. Two examples of applications of the analog FLC SLM presented, one for dynamic DOE's and the other for optical correlators. In both cases, the advantage of the speed due to the FLC is obvious and moreover, the advantage of the pure amplitude modulation over the amplitude phase coupled or the binary modulation has been demonstrated by simulations and also by optical experiments (dynamic DOE's). However, these experimental results only show the potential of the analog FLC SLM, since at the time of this study, only a prototype SLM driver was available; this driver does not linearize the optical response of the SLM and therefore, the gray levels of the input image are not reproduced accurately. The final product driver will be available in May 2001 and much better results should be obtained.

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REFERENCES

- 1. A. VanderLugt, "Signal detection by complex filtering", *IEEE Trans. Inf. Theory* **10**, pp. 139-145, 1964.
- 2. C.S. Weaver and J.W. Goodman, "A technique for optically convolving two functions", *Appl. Opt.* 5, pp. 1248-1249, 1966.
- 3. J.D. Armitage and A.W. Lohmann, "Character recognition by incoherent spatial filtering", *Appl. Opt.* **4**, pp. 461-467, 1965.
- 4. W.P. Bleha, *et al.*, "Application of the Liquid Crystal Light Valve to real-time optical data processing", *Opt. Eng.* **17**, pp. 371-384, 1978.
- 5. Y.E. Nesterkhin, G.W. Stroke and W.E. Kock, *Optical information processing*, Plenum Press, 1976.
- 6. H. Stark, Applications of optical Fourier transforms, Academic Press, 1982.
- 7. S.H. Lee, Optical Information Processing Fiundamentals, Springer-Verlag, 1981.
- 8. INO, "INO Optical correlator OC-VGA-6000", http://www.ino.qc.ca, 2001.

- 9. BNS, "Boulder Nonlinear Systems, Inc; Products", http://www.bnonlinear.com, 2001.
- 10. T.-C. Poon, R. Juday and T. Hara, "Spatial light modulators research, development and applications: introduction to the feature issue", *Appl. Opt.* **37**, pp. 7471, 1998.
- 11. D. Casasent and T.K. Luu, "Photo-DKDP light valve in optical data processing", Appl. Opt. 18, pp. 3307-3314, 1979.
- 12. F. Dumont, J.P. Hazan and D. Rossier, "The Phototitus optical converter", *Philips tech. Rev.* 34, pp. 274-287, 1974.
- 13. S. Iwasa, "Optical processing: near real-time coherent systems using two Itek PROM devices", *Appl. Opt.* **15**, pp. 1418-1424, 1976.
- 14. D.S. Oliver, "Real time spatial light modulators for optical/digital processing systems", *Opt. Eng.* 17, pp. 288-294, 1978.
- 15. B.J. Lechner, F.J. Marlowe, M.E. Nester and J. Tults, "Liquid crystal matrix display", *Proc. IEEE* 59, pp. 1566-1579, 1971.
- 16. G. Labrunie, J. Robert and J. Borel, "A 128 x 128 electro-optical interface for real time data processing", *Revue de Physique Appliquée* **10**, pp. 143-146, 1975.
- D. Casasent, "Performance evaluation of spatial light modulators", *Appl. Opt.* 18, pp. 2445-2453, 1979.
- 18. P. Ambs, Y. Fainman, S.H. Lee and J. Gresser, "Computerized design and generation of space-variant holographic filters. 1: system design considerations and applications of space-variant filters to image processing", *Appl. Opt.* 27, pp. 4753-4760, 1988.
- 19. G.R. Knight, "Interface devices and memory materials", in *Optical Information Processing Fiundamentals*, S.H. Lee ed. Springer-Verlag, pp. 111-179, 1981.
- 20. W.E. Ross and J.A. Davis, "The magneto-optic spatial light modulator", in *Spatial light modulator technology: materials, devices, and applications*, U. Efron ed. Marcel Dekker, Inc., pp. 361-390, 1995.
- 21. W.E. Ross, K.M. Snapp and R.H. Anderson, "Fundamental characteristics of the Litton iron garnet magneto-optic spatial light modulator", *Advances in Optical Information Processing*, SPIE Vol. 388, 1983.
- 22. A.L. Lentine, "Self-electro-optic effect devices for optical information processing", in *Optical Computing Hardware*, J. Jahns & S.H. Lee eds, Academic Press, Inc., pp. 45-72, 1994.
- 23. A.L. Lentine, J.N. Lee, S.H. Lee and U. Efron, "Introduction to the feature on spatial light modulators and their applications", *Appl. Opt.* **33**, pp. 2767, 1994.
- 24. T.-H. Lin, *et al.*, "Two-dimensional spatial light modulators fabricated in Si/PLZT", *Appl. Opt.* **29**, pp. 1595-1603, 1990.
- 25. D.R. Pape and L.J. Hornbeck, "Characteristics of the deformable mirror device for optical information processing", *Opt. Eng.* 22, pp. 675-681, 1983.

- T.G. Mc Donald and L.A. Yoder, "Digital micromirror devices make projection display", *Las. Foc. World* 33, pp. S5-S8, 1997.
- 27. U. Efron, Spatial Light Modulator technology. materials, devices, and applications, Dekker M., New York, 1995.
- 28. "Applied Optics Special Issue on Spatial Light Modulators", *Appl. Opt.* 28, pp. 4739-4908, 1989.
- 29. "Applied Optics Special Issue on Spatial Light Modulators", *Appl. Opt.* **31**, pp. 3876-4041, 1992.
- 30. "Applied Optics Special Issue on Spatial Light Modulators", *Appl. Opt.* **33**, pp. 2767-2860, 1994.
- 31. "Applied Optics Special Issue on Spatial Light Modulators", *Appl. Opt.* **37**, pp. 7471-7552, 1998.
- 32. F.T.S. Yu, S. Jutamulia, T.W. Lin and D.A. Gregory, "Adaptative real-time pattern recognition using a liquid crystal TV based joint transform correlator", *Appl. Opt.* **26**, pp. 1370-1372, 1987.
- 33. F. Mok, J. Diep, H.-K. Liu and D. Psaltis, "Real-time computer generated hologram by means of liquid-crystal television spatial light modulator", *Opt. Lett.* **11**, pp. 748-750, 1986.
- 34. N. Mukohzaka, N. Yoshida, H. Toyoda, Y. Kobayashi and T. Hara, "Diffraction efficiency analysis of a parallel-aligned nematic-liquid-crystal spatial light modulator", *Appl. Opt.* 33, pp. 2804-2811, 1994.
- 35. CRL Opto, "Products Data Sheet", http://www.crlopto.com, 2001.
- 36. Displaytech, "Displaytech Photonics", http://www.displaytech.com, 2001.
- 37. V. Laude, S. Mazé, P. Chavel and P. Réfrégier, "Amplitude and phase coding measurements of a liquid crystal television", *Opt. Commun.* **103**, pp. 33-38, 1993.
- 38. Texas Instrument, "Digital Light Processing", http://www.dlp.com, 2001.
- 39. S.-T. Wu, "Nematic liquid crystal", in *Spatial light modulator technology:* materials, devices, and applications, U. Efron ed. Marcel Dekker, Inc., pp. 1-31, 1995.
- 40. J.S. Patel, S.-D. Lee and J.W. Goodby, "Physical properties of smectic liquid crystal and novel electro-optics effects", in *Spatial light modulator technology: materials, devices, and applications*, U. Efron ed. Marcel Dekker, Inc., pp. 33-83, 1995.
- 41. G. Moddel, "Ferroelectric Liquid Crystal Sapatial Light Modulators", in *Spatial light modulator technology: materials, devices, and applications*, U. Efron ed. Marcel Dekker, Inc., pp. 287-359, 1995.
- 42. J.L. de Bougrenet de la Tocnaye and L. Dupont, "Complex amplitude modulation by use of liquid-crystal spatial light modulators", **36**, pp. 1730-1741, 1997.

- 43. Y. Iwasaki, K. Yoshino, T. Uemoto and Y. Inuishi, "Colour switching in ferroelectric Smectic liquid crystal by electrical field", *Jpn. J. Appl. Phys.* 18, pp. 2323-2324, 1979.
- 44. T. Uemoto, K. Yoshino and Y. Inuishi, "Electric and optical properties of ferroelectric liquid crystals and influence of applied pressure", *Mol. Cryst. Liq. Cryst.* 67, pp. 137-152, 1981.
- 45. S.A. Serati, G.D. Sharp, R.A. Serati, D. McKnight and J.E. Stockley, "128x128 analog liquid crystal spatial light modulator", *Optical pattern recognition VI*, Orlando, D. Casasent & T.-H. Chao eds, SPIE Vol. 2490, pp. 378-387, 1995.
- 46. W.A. Crossland, *et al.*, "Transmissive analogue SLM using a chiral smectic liquid crystal switched by CdSe TFFs", *Liquid-crystal devices and materials*, P.S. Drzaic & U. Efrom eds, SPIE Vol. 1455, pp. 264-273, 1991.
- 47. T.-H. Chao, H. Zhou and G.F. Reyes, "512x512 high-speed grayscale optical correlator", *Optical pattern recognition XI*, Orlando, D. Casasent & T.-H. Chao eds, SPIE Vol. 4043, pp. 40-45, 2000.
- 48. K. Bauchert and S. Serati, "High speed multilevel 512x512 spatial light modulator", *Optical Pattern Recognition XI*, Orlando FL, D. Casasent & T.-H. Chao eds, SPIE Vol. 4043, pp. 59-65, 2000.
- K. Bauchert, S. Serati, G. Sharp and D. McKnight, "Complex phase/amplitude Spatial Light Modulator advances and use in a multispectral optical correlator", *Optical Pattern Recognition VIII*, Orlando FL, D. Casasent & T.-H. Chao eds, SPIE Vol. 3073, pp. 170-177, 1997.
- 50. P. Ambs, L. Bigué and C. Stolz, "Dynamic computer generated hologram displayed on a spatial light modulator for information processing", *III. Euro-American Workshop on Optoelectronic Information Processing*, Colmar (France), P. Refregier & B. Javidi eds, SPIE Vol. CR 74, pp. 151-170, 1999.
- 51. Z. Zhang, G. Lu and F.T.S. Yu, "Simple method for measuring phase modulation in liquid crystal television", *Opt. Eng.* **33**, pp. 3018-3022, 1994.
- 52. M. Yamauchi and T. Eiju, "Optimization of twisted nematic liquid crystal panels for spatial light phase modulation", *Opt. Commun.* **115**, pp. 19-25, 1995.
- 53. J. Colin, "Corrélation optique photoréfractive haute cadence à transformée de Fourier conjointe", Thesis, Université de Paris VI, 1998.
- 54. C. Soutar and K. Lu, "Determination of the physical properties of an arbitrary twisted-nematic liquid crystal cell", *Opt. Eng.* 33, pp. 2704-2712, 1994.
- 55. K. Lu and B. Saleh, "Theory and design of the liquid crystal TV as an optical spatial phase modulator", *Opt. Eng.* **29**, pp. 240-246, 1990.
- 56. I. Labastida, A. Carnicer, E. Martin-Bodosa, S. Vallmitjana and I. Juvells, "Optical correlation by use of partial phase-only modulation with VGA liquidcrystal display", *Appl. Opt.* **39**, pp. 766-769, 2000.
- 57. I. Abdulhalim, "Continuous phase-only or amplitude light modulation using ferroelectric liquid crystals with boundary orientation", *Opt. Commun.* **108**, pp. 219-224, 1994.

- 58. F. Wyrowski and O. Bryngdahl, "Iterative Fourier-transform algorithm applied to computer holography", J. Opt. Soc. Am. A 5, pp. 1058-1065, 1988.
- 59. J.L. Horner and P.D. Gianino, "Phase-only matched filtering", *Appl. Opt.* 23, pp. 812-816, 1984.
- 60. S. Maze and P. Réfréfier, "Optical correlation: influence of the coding of the input image", *Appl. Opt.* **33**, pp. 6788-6796, 1994.
- L. Bigué and P. Ambs, "Filter Implementation technique for multicriteria characterization of coding domains in the joint transform correlator", *Appl. Opt.* 38,, 1999.
- 62. E. Hueber, L. Bigué, P. Réfrégier and P. Ambs, "Optical implementation of a snake-based segmentation with an incoherent correlator", *Aerosense 2001,Optical Pattern Recognition XII*, Orlando (USA), D. Casasen & T.-H. Chao eds, SPIE Vol. 4387, pp. 87-94, 2001.
- 63. V. Laude and P. Réfrégier, "Multicriteria characterization of coding domains with optimal Fourier SLM filters", *Appl. Opt.* **33**, pp. 4465-4471, 1994.
- 64. R. Juday, "Philosophy for optical filter optimization", *Euro American Workshop* on Optoelectronic Information Processing, Colmar, P. Réfrégier & B. Javidi eds, SPIE Critical Review Vol. CR74, pp. 227-240, 1999.
- 65. R.D. Juday, "Optimal realizable filters and the minimum Euclidean distance principle", *Appl. Opt.* **32**, pp. 5100-5111, 1993.
- 66. L. Bigué and P. Ambs, "Implementation of optimal trade-off correlation filters with an optimized resolution technique", *J. Opt. A: Pure Appl. Opt.* **1**, pp. 280-282, 1999.
- 67. P. Réfrégier, "Optimal trade-off filters for noise robustness, sharpness of the correlation peak, and Horner efficiency", *Opt. Lett.* 16, pp. 829-831, 1991.
- 68. G. Ravichandran and D.P. Casasent, "Minimum noise and correlation energy optical correlation filter", *Appl. Opt.* **31**, pp. 1823-1833, 1992.
- 69. B.V.K. Vijaya Kumar, "Tutorial survey of composite filter designs for optical correlators", *Appl. Opt.* **31**, pp. 4773-4801, 1992.
- 70. B. Javidi and C.-J. Kuo, "Joint transform image correlation using a binary spatial light modulator at the Fourier plane", *Appl. Opt.* 27, pp. 663-665, 1988.
- 71. P. Réfrégier, V. Laude and B. Javidi, "Basic properties of nonlinear global filtering techniques and optimal discriminant solutions", *Appl. Opt.* 34, pp. 3915-3923, 1995.

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