Optical Correlator with Fully Complex Liquid Crystal Filter

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ABSTRACT:

A fully complex filter is discussed using a Boulder Nonlinear Systems Smectic A* liquid crystal spatial light modulator. Each pixel is capable of both analogue amplitude modulation and binary phase modulation. Two pixels are used together in a macro pixel giving full complex modulation.

Keywords: Correlators, Complex Modulation

1. INTRODUCTION

Optical correlators provide the means of very fast real time pattern recognition. The filter used in real time applications is often implemented with a binary phase modulating ferroelectric liquid crystal (LC) spatial light modulator (SLM). Such systems are based on the VanderLugt¹ design. Since the filter function is approximated by the SLM, there is an inevitable deterioration in performance of the system. It would be better in principle to use a fully complex filter in place of the binary SLM. This would more closely match the ideal filter.

We report on a correlator system utilising a complex frequency plane filter. This was implemented with an analogue ferroelectric liquid crystal (AFLC) SLM from Boulder Nonlinear Systems (BNS). This was set up in such a way to give full complex modulation by combining two pixels that modulated along the real axis using a phase detour technique. This technique is similar to work by others but only uses two pixels instead of the more usual four^{2,3,4,5} and is developed from work used to produce complex holograms⁶. Other techniques using two SLMs⁷ or deformable mirror devices^{8,9} are also possible.

2. THEORY

The SLM used in the experimental work was the Boulder Nonlinear System 128x128 analogue (8 bit resolution) silicon back-plane device driven by a PC. The liquid crystal material used by this SLM was in the Smectic A* phase which can be used to provide a variety of different modulations including: phase only, amplitude only and analogue positive and negative modulation along the real axis¹⁰. The real axis modulation is achieved by placing the reflective SLM in front of a polarising beam splitter (see figure 1). The device specifications are shown in table 1.

Parameter	Specification
Liquid crystal type	Smectic A*
Total array size	5.12mm x 5.12 mm
Number of pixels	16 384 (128x128 in square format)
Pixel fill factor	60%
Frame load time	100µs
Resolution	8-bit (256 levels)
Liquid crystal response time (10%-90%)	As short as 200ns depending on temperature

Table 1. Device specifications.

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Figure 1a) Optical system to produce real axis modulation. b) Simulation of device modulation along real axis as liquid crystal tilt axis moves from $-\pi/8$ to $\pi/8$.

The AFLC can be thought of as a waveplate with a fixed retardance, but with the optical axis being capable of rotation between $\pm\pi/8$ radians by application of an electric field. The incident light is linearly polarised at an angle that bisects the two extreme angles of the AFLC's optical axes and an orthogonal polariser is placed at the output. The Jones' matrix for such an arrangement is similar to a conventional smectic C* SLM, i.e.,

$$\mathbf{T} = \begin{bmatrix} \exp(-i\Gamma/2)\cos\theta\sin\theta & -\exp(i\Gamma/2)\cos\theta\sin\theta \\ 0 & 0 \end{bmatrix} \quad (1)$$

where Γ is the retardance of the device, which is fixed, and θ is the angle of the optical axis. The transmission of the SLM can then be varied by application of an electric field, which alters the value of θ . The phase shift of the light, dependant on the sign of θ , is $\pm\pi/2$ radians which is the equivalent of a 0 to π phase shift since the absolute phase angle is unimportant. This results in bipolar analogue modulation along the real axis.

To achieve complex modulation, it is also necessary to modulate along the imaginary axis. This was achieved by combining two pixels of the SLM. One pixel contained the real data and second pixel contained the imaginary data. Modulation of the imaginary axis can be achieved by imposing a $\pi/2$ phase difference relative to the pixel containing the real data. The phase shift between the two pixels can be achieved by tilting the SLM by an angle such that one pixel has a phase lag of $\pi/2$ relative to its adjacent pixels (see figure 2). From figure 2 it can be seen that with this method the next real axis pixel will be π out of phase with the first. This leads to an undesirable second reconstruction in the output plane. To overcome this, the data on every second real and imaginary pixels is multiplied by -1 by exploiting the bipolar ability of the device. In practice, it is not necessary to physically introduce a tilt of the required amount on to the SLM since the reconstruction will instead appear off axis. This angle is exactly half way between the zeroth order and the first order replication of the DC term.

Figure 2. Phase detour technique for implementing fully complex filter. The real data, R_n is combined with the imagery data I_n . Reconstruction occurs off axis when there is a $\pi/2$ phase difference between the real and imaginary pixels. Every second macro pixel is negative to remove a π discontinuity that would otherwise occur.

The separation of the macro pixels is a in the horizontal direction. The complex spectrum $f(x,y)$ placed onto the SLM becomes sampled as

$$f_s = \text{comb}\left(\frac{y}{b}\right) \sum_{n=-\infty}^{\infty} \delta(x-na) \text{Re}[f(x,y)] \exp(i\pi n) + \text{comb}\left(\frac{y}{b}\right) \sum_{n=-\infty}^{\infty} \delta\left(x-a\left(n+\frac{1}{2}\right)\right) \text{Im}\left[f\left(x-\frac{a}{2}, y\right)\right] \exp(i\pi n) \quad (2)$$

where $b = \frac{a}{2}$, since we have not doubled the pixels up in to pairs in the y direction. For the BNS SLM, a is $80\mu\text{m}$.

$$f_s = \frac{1}{2} \left(\text{comb}\left(\frac{x}{2a}, \frac{y}{b}\right) - \text{comb}\left(\frac{x-a}{2a}, \frac{y}{b}\right) \right) f(x,y) + \frac{1}{2} \left(\text{comb}\left(\frac{x}{2a}, \frac{y}{b}\right) - \text{comb}\left(\frac{x-a}{2a}, \frac{y}{b}\right) \right) f^*(x,y) + \frac{1}{2} \left(\text{comb}\left(\frac{x-a/2}{2a}, \frac{y}{b}\right) - \text{comb}\left(\frac{x+a/2}{2a}, \frac{y}{b}\right) \right) f\left(x-\frac{a}{2}, y\right) - \frac{1}{2} \left(\text{comb}\left(\frac{x-a/2}{2a}, \frac{y}{b}\right) - \text{comb}\left(\frac{x+a/2}{2a}, \frac{y}{b}\right) \right) f^*\left(x-\frac{a}{2}, y\right) \quad (3)$$

The Fourier transform of equation [3] is

$$F_s(\omega) = \frac{1}{2} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} F\left(\omega_x - \frac{n}{2a}, \omega_y - \frac{m}{b}\right) (1 + \exp(-i\pi a \omega_x)) (1 - \exp(i\pi n)) + \frac{1}{2} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} F^*\left(-\omega_x - \frac{n}{2a}, \omega_y - \frac{m}{b}\right) (1 - \exp(-i\pi a \omega_x)) (1 - \exp(i\pi n)) \quad (4)$$

Which only exists when n is odd. The $(1 \pm \exp(-i\pi a \omega_x))$ term acts as an intensity modulation function across the output field. This causes the real and conjugate terms alternatively to be blanked.

3. EXPERIMENTAL

The system has been set up in a conventional all optical 4-f correlator (see figure 3), using the AFLC SLM in the filter plane. A photographic negative was used to produce the input mask, but the optics has been designed so that the two identical SLMs can be used; one acting as the input mask while the other is the filter. Since the BNS SLMs have both digital inputs as well as digital DALSA camera inputs, this will allow for future upgrades to high speeds.

Figure 3. The optical layout for the correlator system. The FT lens has an 800mm focal lens. PBS: polarising beam splitter. The CCD camera grabs the correlation peak.

4. RESULTS

To evaluate the performance of the filter, the real-only filter and complex filter were compared. Figure 4a) shows in the input filter function. A real-only filter for the letter A was placed on the SLM corresponding to the real component of the complex Fourier spectrum. The correlation peaks generated by this are shown in figure 4b). Since the filter is real-only it can not distinguish between the two different orientations of the letter A due to the symmetry of the real-only Fourier transform; hence the two correlation spots. Figure 4c) shows the same input but with the complex filter. The top A is now rejected and only one correlation spot is visible. Figure 4d) is another example of correlation, in this case the system is distinguishing the letter O from an X. Because of the relatively low efficiency of the device, the back reflection off the SLM is also visible.

Figure 4. a) The input function. b) The real-only filter c) The complex filter correlation. d) Another example of the complex filter, in this case an *O* is detected and the *X* is rejected. Note the filter is rotated 90° compared to the first example, so the peak appears below the object.

5. DISCUSSION

Two correlation peaks are clearly visible in the real-only filter (figure 4b)) which is what was expected. A single peak is visible in figure 4c) and d) demonstrating the complex nature of the filter. In figure 4c) the cross correlation of the letter A is also visible above the correlation peak. The back reflections of the input mask are also slightly visible in the left-hand part of the image. These are likely to occur because of the low optical efficiency of the SLM and possibly also due to calibration errors resulting in not all of the light being diffracted out of the input image. The correlation spot is shifted off axis because of the carrier frequency method used in encode the fully complex data on the SLM. In figure 4d) the correlation spot is below the object instead of to the right; this is simply because the filter was rotated 90° with respect to the other examples.

Although this method only requires 2 pixels to encode the data, 4 are used in a 2×2 square so that the sampling rate is the same in both directions on the SLM. This effectively reduces the resolution of the SLM to 64×64 pixels. There is no reason why the filter could not use a 2×1 macro pixel provided the sampling of the initial Fourier transform used to produce the filter function took this in to account.

The current system is limited by the resolution of the SLM. BNS will be introducing a 512×512 SLM in the near future and this will be then used in future correlators. To remove the problem of the different sampling rates in x and y directions, the SLM pixels would ideally have a 2:1 rectangular aspect ratio.

6. CONCLUSIONS

A correlator system with a high-speed fully complex filter has been experimentally demonstrated. The filter is based on an SLM that produces a real axis modulation but unlike a real only filter it can distinguish between two objects rotated 180 degrees.

7. ACKNOWLEDGEMENTS

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