Dynamic Complex Wavefront Modulation with an Analogue Spatial Light Modulator

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Abstract

A method of producing an arbitrary complex field modulation using two pixels of an analogue ferroelectric SLM is demonstrated. The method uses the grey scale modulation capabilities of an SLM to spatially encode the complex data on two pixels. A spatial filter was used to remove the carrier signal. This gives fast grey level amplitude and phase modulation.

Introduction

Complex field modulation by liquid crystal (LC) spatial light modulators (SLM) has a variety of uses. They have in the past been used for correlator filters, 3D displays, computer generated holograms and turbulence simulation [1]. This has traditionally been limited to either phase only modulation or amplitude only modulation using either nematic, or ferroelectric LC (FLC) SLMs. Nematic SLMs suffer from the relative slow speed; FLCs are considerably faster but are binary devices. It would be of considerable interest to have a device that can modulate phase and amplitude together at a high frame rate.

Several authors have demonstrated methods of producing full complex modulation. Examples of these methods are the cascading of two SLMs [2], phasor combination of two pixels [3] and computer generated holograms [4]. Each of these methods have problems associated with them. Cascading requires two SLMs so it is expensive and physically bulky and computer generated Fourier holographic methods may produce a very noisy intensity fields due to the limited number of pixels available on current SLMs. In this letter, a 2 pixel encoding method will be used to modulate light. Both amplitude and phase data can be modulated simultaneously.

Theory

The SLM used is a Boulder Nonlinear Systems analogue ferroelectric (AFLC) SLM. The device has 128x128 pixels with a 40μm pixel pitch and can modulate with 8 bit accuracy (256 grey levels). The electronic load time is 102μm and the LC switching time is quoted at about 50 -150μS [5] (depending on temperature). This makes the device ideal for high - speed applications such as a filter implementation in optical correlators.

Conceptually each pixel acts as a half wave plate with an optical axis that can be rotated electronically. To get real axis modulation, a linear input polarisation state is required at an angle that bisects the two extremes of the liquid crystals possible axes. The transmitted amplitude, $A(\theta)$, can then be simply derived using Jone's calculus as

$$A(\theta) = \sin\left(\Gamma/2\right)\cos(\theta)\sin(\theta) \qquad [1]$$

where a common phase term has been dropped, Γ is the retardance of the SLM and θ is the angle of the optical axis of the LC compared to the input polarisation axis. Γ is nominally π but in reality will deviate slightly from this. Since the sin(θ) term in [1] is an odd function and θ is in the range $\theta_{min} \le \theta \le \theta_{max}$ where θ_{min} is negative and θ_{max} is positive, $A(\theta)$ can be either positive and negative. With this ability a complex number can be represented using only two pixels, as opposed to 3 or 4 using intensity only modulating phase detour techniques and with no DC bias. The grey level ability of the pixels also increases the total resolution of the system when compared to binary FLC devices.

The encoding method is based on the authors' earlier work on two pixel computer generated holograms [6]. However, holographic techniques are not suitable for all applications. Uniform intensity patterns become very noisy and so phase only pattern would be difficult to represent.

The method encodes the imagery data by creating a π/2 phase lag between the real data by laterally shifting the data on e pixel in the space domain. That is, the real data is placed on the pixel next to the imaginary. Every second group of pixels is negated to remove a π discontinuity that would otherwise occur. The encoded signal is then spatially filtered to remove the encoding artefacts.

The complex signal, f(x,y) is written to the SLM, as f_s, and is represented by

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

where a is the width of the macro pixel, i.e., two pixels in the x direction
The Fourier transforms of [2] is

$$F_s(\omega_x,\omega_y)=\frac{1}{2}\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}F\left(\omega_x-\frac{n}{2a},\omega_y-\frac{m}{b}\right)(1+\exp(-i\pi a\omega_x))(1-\exp(i\pi n))+ \frac{1}{2}\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}F^*\left(-\omega_x-\frac{n}{2a},-\omega_y-\frac{m}{b}\right)(1-\exp(-i\pi a\omega_x))(1-\exp(i\pi n)) \qquad [3]$$

So the Fourier transform of $f(x,y)$ appears shifted of axis when n=1,5,7… and n=-3,-7… and the conjugate terms appear when n=-1,-5,-7 and n=3,7… Selecting one (n=1) of these replications by inserting a mask in the Fourier plane reduces [3] to

$$F(\omega_x,\omega_y)=\frac{1}{2}\begin{bmatrix}F(\omega_x,\omega_y)\left(1+\exp(i\pi a\omega_x)\exp\left(-i\pi/2\right)\right)+\\ F^*(-\omega_x,-\omega_y)\left(1-\exp(i\pi a\omega_x)\exp\left(-i\pi/2\right)\right)\end{bmatrix}\mathrm{rect}(\omega_x a,2\omega_y a) \quad [4]$$

Here the co -ordinate system has been re -centred on the centre of first replication. This removes the phase wedge that would otherwise occur when [4] is again Fourier transformed. The Fourier transform of [4] is then

$$f_r(x,y)=\left\{\mathrm{Re}[f(x,y)]+i\,\mathrm{Im}\left[f\left(x+a/2,y\right)\right]\right\}\otimes\frac{1}{2|a|^2}\mathrm{sinc}\left(\frac{x}{a},\frac{y}{2a}\right) \quad [5]$$

which gives the reconstruction in the output. The introduction of the rectangular aperture halves the resolution such that the spatial shift between the real and imaginary components, $a/2$ (which is one pixel), can no longer be resolv ed in the x direction giving full complex modulation.

The experimental set up to produce complex modulation and quantify it is shown in figure 1. The light source was a CW frequency doubled YAG laser operating at 532nm. The system is set up as a Mach -Zender interferometer to measure the phase modulating ability. The lenses L1 and the mask M are the spatial filter system that removes the conjugate terms.

The complex field was measured in two ways. Complex amplitude only data was written to the SLM. This consisted of the amplitude mask of the white letter A on a black background. This was encoded and written to the SLM as shown in figure 2. The intensity distribution in the image plane was imaged by a camera and is shown in figure 3. The top arm of the Mach -Zender in figure 1 blocked for this demonstration. It can be seen that the encoding artefacts in figure 2 have been completely removed by the spatial filtering.

To demonstrate the phase modulating characteristics of the method, a phase only array was generated which consisted of a vertical bar π phase shifted with respect to the rest of the field. This was then encoded and written on the SLM. The upper arm of the system in figure 1 was unblocked making a Mach-Zender interferometer. The lenses marked L2 were needed to invert the reference beam to the same orientation as the object beam, this also matched both the path lengths and spherical aberrations introduced by lenses L1. Since the output polarisation from the SLM is orthogonal to the input a half-wave plate was introduced. This could then rotated to finely balance the amplitudes along each arm of the interferometer to maximise the fringe contrast.

An image of the unfiltered amplitude data distribution actually written to the SLM is shown in figure 4 and the filtered interferogram showing the phase shift is shown in figure 5.

Conclusion

A method of complex field modulation has been demonstrated. The technique uses a two pixel encoding method and spatial filtering. Both amplitude modulation and phase modulation have been demonstrated experimentally.

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Figure Captions

Figure 1. Experimental setup. HWP: half wave plate, BS beam splitter, POL: polariser, L1 and L2: 250mm focal length lenses. PBS: polarising beam splitter, M: spatial filter mask. The upper arm of the interferometer was blocked when amplitude only measurements were made.

Figure 2. The letter A encoded and displayed on the SLM without the spatial filtering.

Figure 3. The letter A encoded and spatially filtered to get complex modulation.

Figure 4. A vertical bar π phase shifted and encoded on the SLM with out the spatial filter.

Figure 5. An interferogram of a π phase shifted bar.

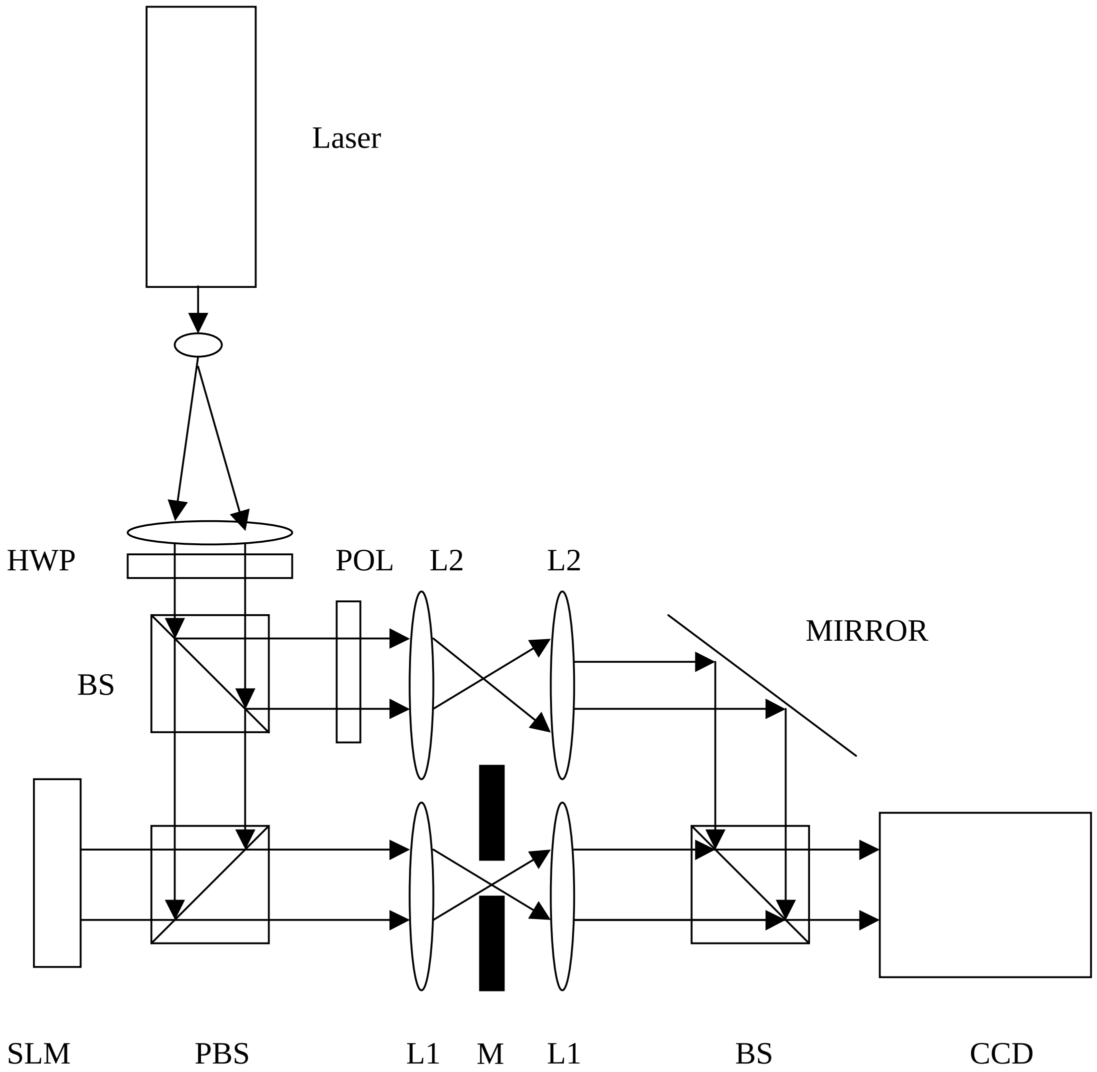

Figure 1 Birch

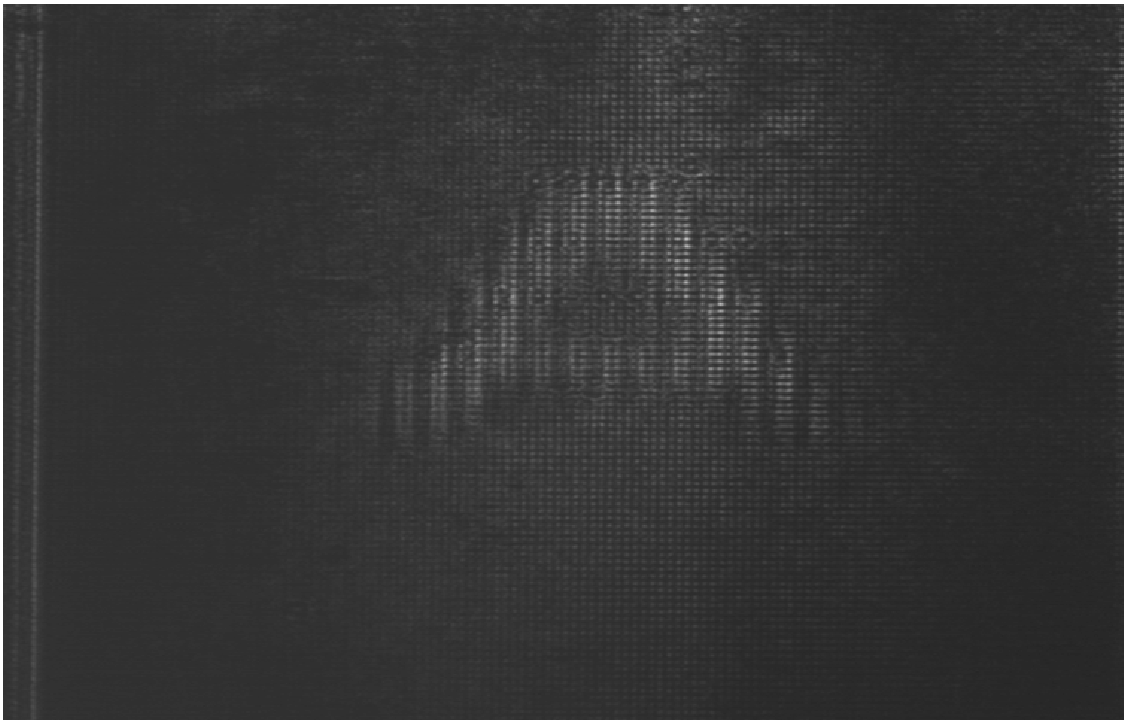

Figure 2 Birch

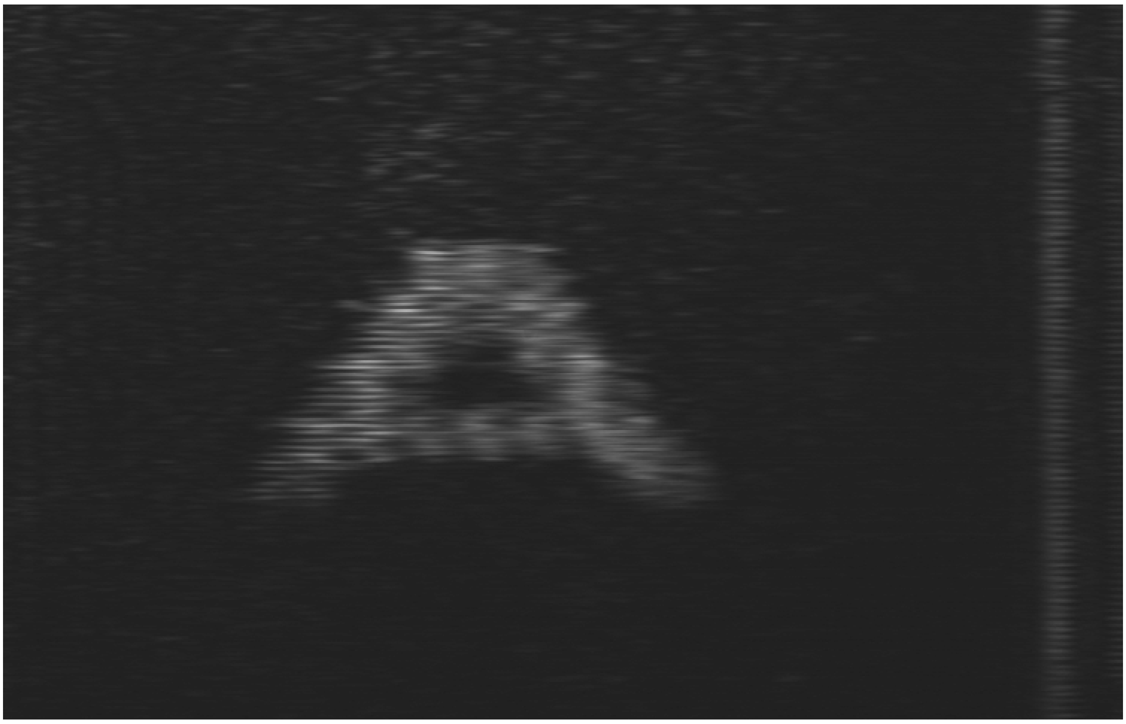

Figure 3 Birch

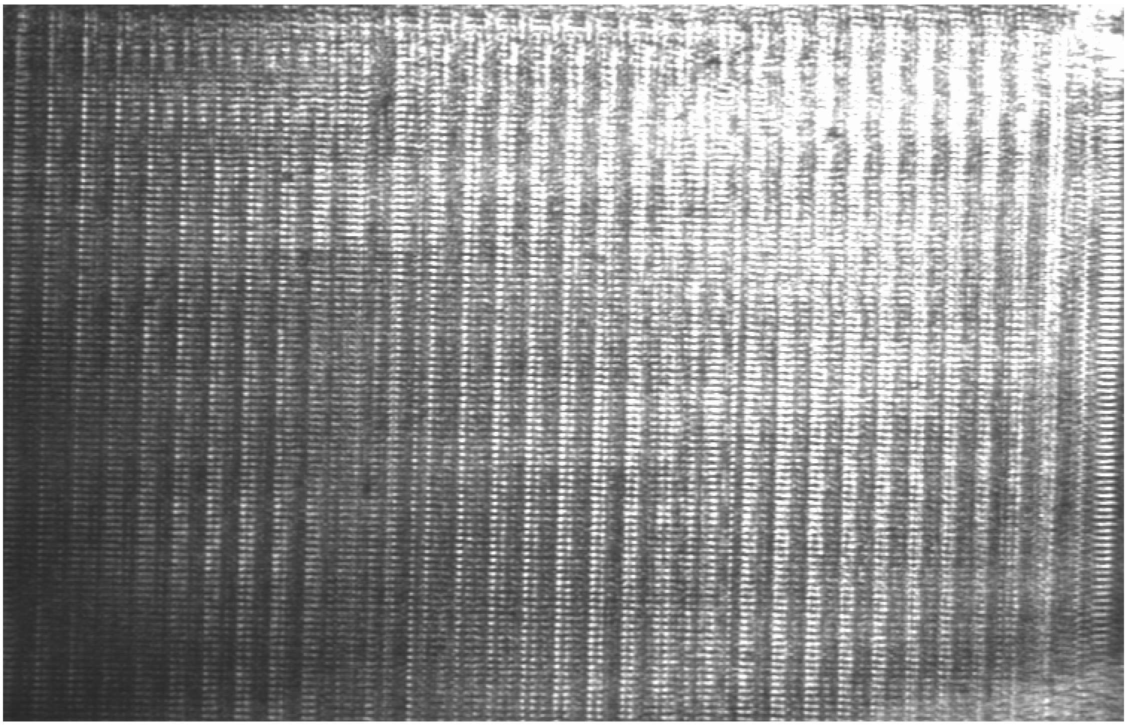

Figure 4 Birch

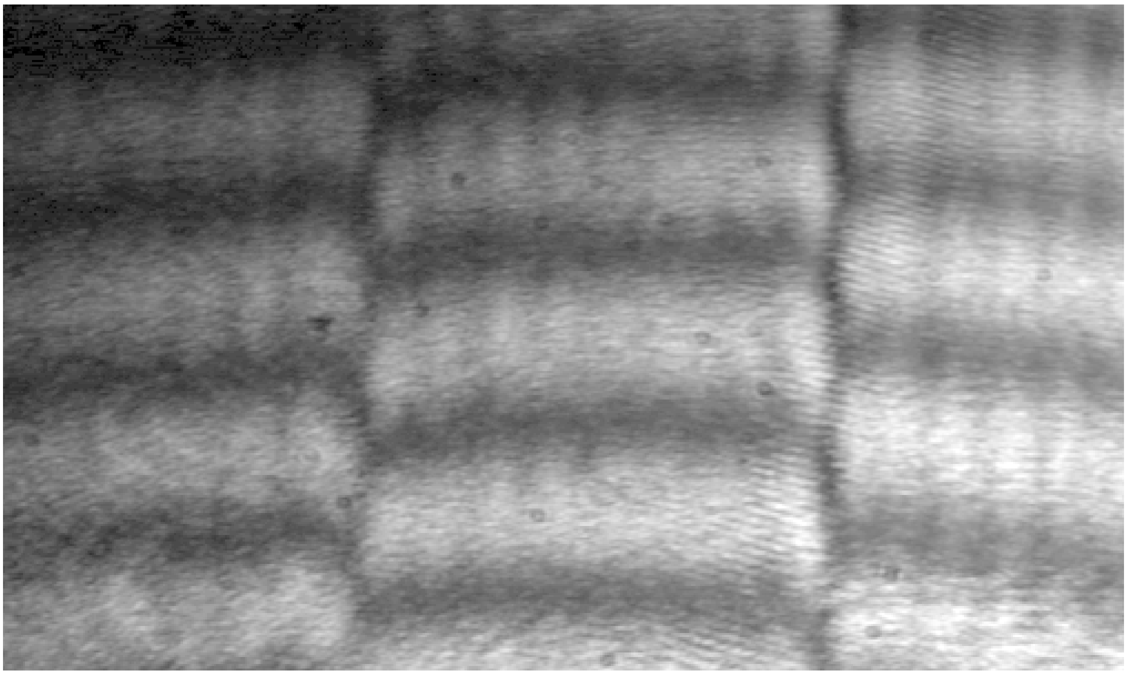

Figure 5 Birch