Dynamic complex wave-front modulation with an analog spatial light modulator

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A method of producing an arbitrary complex field modulation by use of two pixels of an analog ferroelectric spatial light modulator (SLM) is demonstrated. The method uses the gray-scale modulation capabilities of a SLM to spatially encode the complex data on two pixels. A spatial filter is used to remove the carrier signal. This technique gives fast gray-level amplitude and phase modulation. © 2001 Optical Society of America

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Complex field modulation by liquid-crystal (LC) spatial light modulators (SLMs) has a variety of uses. These SLMs been used in the past for correlator filters, three-dimensional displays, computer-generated holograms, and turbulence simulation.[1] This modulation has traditionally been limited to either phase-only or amplitude-only modulation by use of either nematic or ferroelectric liquid-crystal (FLC) SLMs. Nematic SLMs suffer from relatively 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 cascading of two SLMs,[2] phasor combination of two pixels,[3] and computer-generated holograms.[4] Each of these methods has problems associated with it. Cascading requires two SLMs, so it is expensive and physically bulky, and computer-generated Fourier holographic methods can produce very noisy intensity fields, owing to the limited number of pixels available on current SLMs. In this Letter a two-pixel encoding method is used to modulate light. Both amplitude and phase data can be modulated simultaneously.

The SLM used is a Boulder Nonlinear Systems analog FLC SLM. The device has 128×128 pixels with a 40-μm pixel pitch and can modulate with 8-bit accuracy (256 gray levels). The electronic load time is 102 μm, and the LC switching time is quoted at approximately 50–150 μs (depending on temperature).[5] These load and switching times make the device ideal for high-speed applications such as 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 requires a linear input polarization state at an angle that bisects the two extremes of the LC's possible axes. The transmitted amplitude, $A(\theta)$, can then be simply derived by use of Jones calculus as

$$A(\theta) = \sin(\Gamma/2)\cos(\theta)\sin(\theta), \tag{1}$$

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 with the input polarization axis. Γ is nominally π but in reality will deviate slightly from this value. Since the $\sin(\theta)$ term in Ref. 1 is an odd function and θ is in the range $\theta_{\min} \le \theta \le \theta_{\max}$, where $\theta_{\min}$ is negative and $\theta_{\max}$ is positive, $A(\theta)$ can be either positive and negative. With this ability one can represent a complex number using only two pixels, as opposed to three or four with intensity-only modulating phase detour techniques and with no dc bias. The gray-level ability of the pixels also increases the total resolution of the system compared with that of 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 a phase-only pattern would be difficult to represent.

The method encodes the imagery data by creating a $\pi/2$ phase lag between the real data by laterally shifting the data by one pixel in the space domain. That is, the real data are placed on the pixel to the imaginary. Negating every second group of pixels removes a π discontinuity that would otherwise occur. The encoded signal is then spatially filtered for removal of the encoding artifacts.

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

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

where a is the width of the macro pixel, i.e., two pixels in the x direction. The Fourier transform of Eq. (2) is

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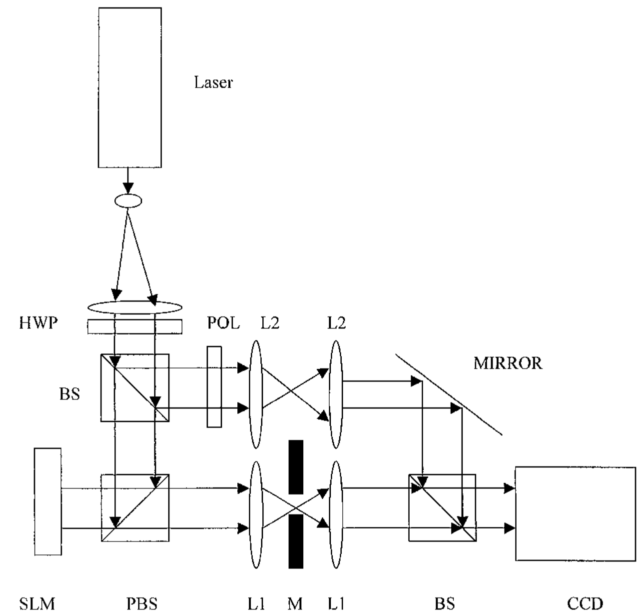

Fig. 1. Experimental setup: HWP, half-wave plate; BSs beam splitters; POL, polarizer; L1, L2, 250-mm focal-length lenses; PBS, polarizing beam splitter; M, spatial filter mask. The top arm of the interferometer was blocked when amplitude-only measurements were made.

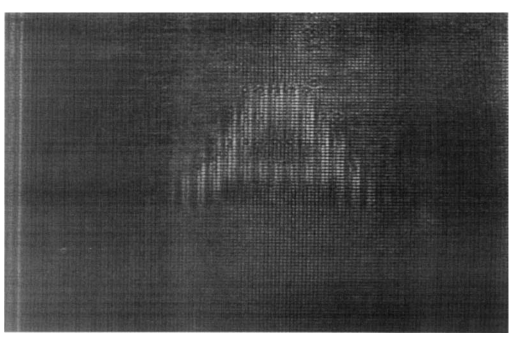

Fig. 2. Letter A encoded and displayed on the SLM without spatial filtering.

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

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

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

Here the coordinate system has been recentered on the center of first replication. This recentering removes the phase wedge that would otherwise occur when Eq. (4) is again Fourier transformed. The Fourier transform of Eq. (4) is then

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

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 the imaginary components, $a/2$ (which is one pixel), can no longer be resolved in the x direction, giving full complex modulation.

The experimental setup used to produce complex modulation and quantify it is shown in Fig. 1. The light source was a cw frequency-doubled yttrium aluminum garnet laser operating at 532 nm. The system is set up as a Mach–Zender interferometer to measure the phase-modulating ability. Lenses L1 and mask M are the spatial filter system that removes the conjugate terms.

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

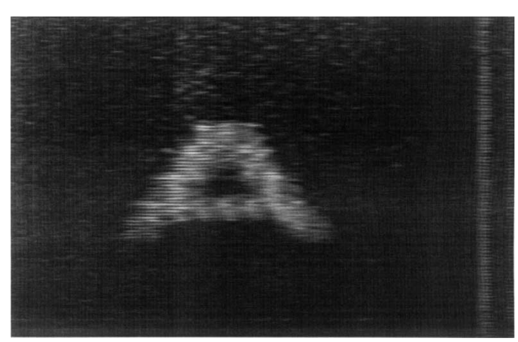

Fig. 3. Letter A encoded and spatially filtered to get complex modulation.

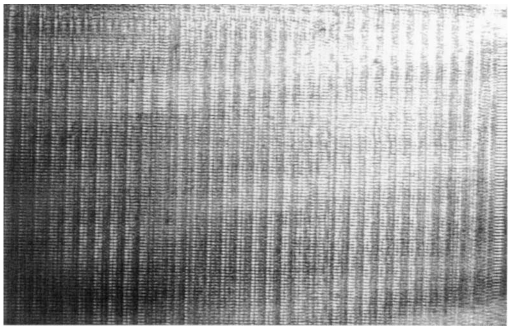

Fig. 4. Vertical bar π phase shifted and encoded on the SLM with out the spatial filter.

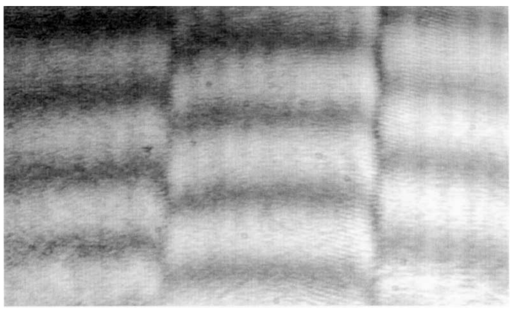

Fig. 5. Interferogram of a π phase-shifted bar.

To demonstrate the phase-modulating characteristics of the method, we generated a phase-only array that consisted of a vertical bar that was π phase shifted with respect to the rest of the field. This bar was then encoded and written to the SLM. The top arm of the system in Fig. 1 was unblocked, making a Mach–Zender interferometer. Lenses L2 were needed to invert the reference beam to the same orientation as the object beam; this also matched the path lengths of both beams and the spherical aberrations introduced by lenses L1. Since the output polarization from the SLM was orthogonal to the input, a half-wave plate was introduced. This plate could then rotated to finely balance the amplitudes along each arm of the interferometer to maximize the fringe contrast. An image of the unfiltered amplitude data distribution that was actually written to the SLM is shown in Fig. 4, and a filtered interferogram showing the phase shift is shown in Fig. 5.

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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