

Full complex modulation using liquid-crystal televisions

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An optical architecture is proposed that uses two modified liquid-crystal televisions (LCTV's) to control amplitude and phase modulation independently. Two applications in pattern recognition are discussed.

Liquid-crystal televisions (LCTV's) have been popular for several years as amplitude-modulating spatial-light modulators and recently the phase-modulating properties of these devices have also been measured and exploited. This Note completes the picture by describing how a pair of LCTV's can be used to produce a single image with both phase and amplitude modulation. There are at least two architectures for accomplishing this task. The first is shown in Fig. 1(a).¹ The beam splitter that produces the two addressing beams is not shown. Ultimately the LCTV's could be bonded to the beam splitter itself. Careful examination of this architecture shows that the resulting image is

$$m(x, y) = Af(x, y) + \exp[jBg(x, y)], \quad (1)$$

where $m(x, y)$ is a complex image formed by the coherent addition of purely phase and purely amplitude images. Any desired complex function could be achieved with the correct choice of $f(x, y)$ and $g(x, y)$. The coefficients A and B are device-specific parameters.

A much simpler method to achieve the desired complex image is shown in Fig. 1(b). The first LCTV is arranged between two flat sheet polarizers to achieve amplitude modulation, while allowing LCTV's to be placed close to one another. It is assumed that the LCTV's will be close enough to avoid diffraction effects between the two devices. If this is not the case, the first LCTV can be imaged 1:1 onto the second LCTV to avoid this problem. The second LCTV modulates phase and the two images are combined in a multiplicative operation given by

$$k(x, y) = Af(x, y)\exp[jBg(x, y)]. \quad (2)$$

This architecture has two distinct advantages over the

system shown in Fig. 1(a). The alignment is much easier to perform in a common-path architecture and the choice of $f(x, y)$ and $g(x, y)$ is much easier to make. All the phase information is contained in the second modulator [displaying $g(x, y)$] and all of the amplitude information is contained in the first modulator [displaying $f(x, y)$]. This is not true for the system described by Eq. (1). The phase term $g(x, y)$ contributes to both the amplitude and the phase of $m(x, y)$ and, in like manner, the amplitude term $f(x, y)$ contributes to both components.

The modulation characteristics of several liquid-crystal devices, including the Seiko LVD202 and the Epson Crystal Image LCTV's, were described previously in some detail.^{2,3} It was shown in these papers that the Epson LCTV can modulate in excess of 235 deg of phase and achieve a visibility of 0.96. These properties can be combined as described above to achieve a complex image with independently controllable phase and amplitude. The phase-shift property was measured by displaying an alternating series of bright and dark bars on the LCTV. The image of this pattern served as one leg of a Mach-Zehnder interferometer. A photograph depicting the phase shift between the bright and dark bars displayed on the Epson LCTV is shown in Fig. 2(a). Figure 2(b) is a photograph of the same bar pattern displayed in amplitude on the Epson LCTV.

The architecture presented in Fig. 1(b) lends itself to immediate application in optical filtering. This architecture will provide a fully programmable, updatable, full complex filter for use in any optical system. Optical correlation filters can now extend beyond binary-phase-only to the multilevel phase-multilevel amplitude filter.

Consider the system in Fig. 3 and assume that a digital filter has been calculated with an amplitude and phase given by

$$H(u, v) = |H(u, v)|\exp[j\phi_H(u, v)], \quad (3)$$

where u and v are the coordinates in the Fourier-transform plane. The inverse transform of this filter is

$$F^{-1}[H(u, v)] = h(x, y), \quad (4)$$

and the spatial frequencies are given by

$$\Omega_x = u/\lambda f, \quad \Omega_y = v/\lambda f, \quad (5)$$

where λ is the wavelength of the coherent illumination and f is the focal length of the Fourier-transform lens. The magnitude of this filter, $|H(u, v)|$, is displayed on LCTV1 [becoming $f(x, y)$], while the phase is displayed on LCTV2 [becoming $g(x, y)$]. Now assume that the light addressing

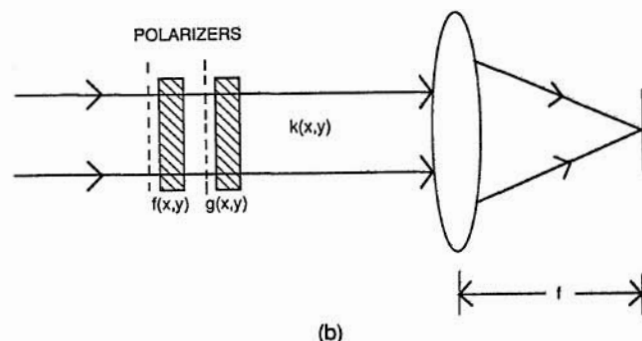
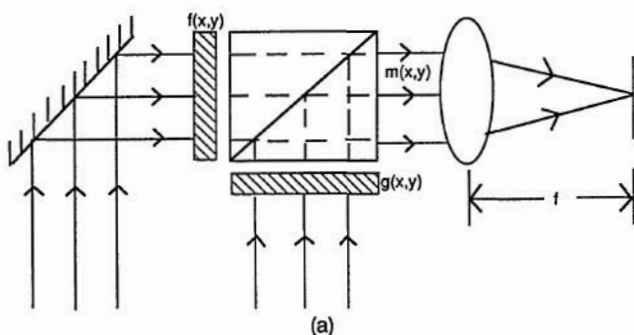


Fig. 1. (a) Architecture for combining amplitude and phase as a sum, (b) architecture for combining amplitude and phase as a product.

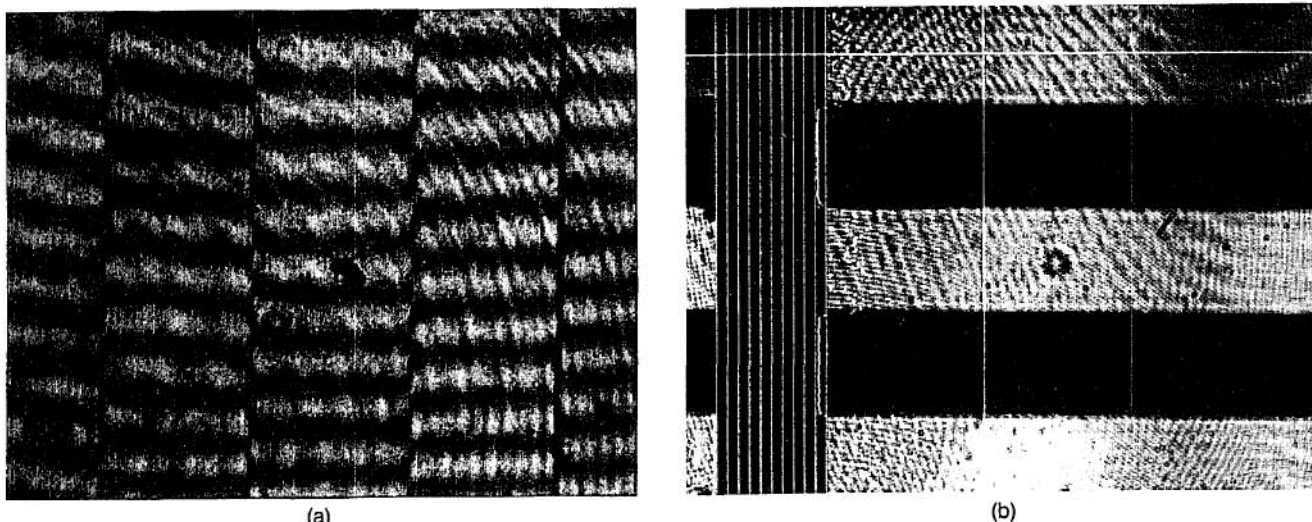


Fig. 2. (a) Phase modulation from an LCTV, (b) Amplitude modulation from an LCTV.

the first LCTV has the form

$$S(u, v) = F[s(x, y)], \quad (6)$$

where $F\{\}$ denotes the Fourier transform and $s(x, y)$ is an input scene not necessarily identical to $h(x, y)$. Immediately after LCTV1, the field is

$$U_1(u, v) = S(u, v)|H(u, v)|. \quad (7)$$

This is then mapped 1:1 to the second LCTV so that the field after the second LCTV is given by

$$U_2(u, v) = S(u, v)|H(u, v)|\exp[j\phi_H(u, v)] = S(u, v)H(u, v). \quad (8)$$

The final lens takes the inverse transform of U_2 :

$$U_3(x', y') = s(x, y) * h(x, y). \quad (9)$$

The resultant field is simply the convolution of $s(x, y)$ with a filter function $h(x, y)$. The proper choice of $h(x, y)$ will result in an autocorrelation, cross correlation, or any other filtering function. This technique can successfully implement any filter function that can be described within the amplitude and phase limits of the LCTV or any other modulator, such as the deformable mirror device, which is known to modulate amplitude and phase.⁴

One concern of this approach is that the amplitude-modulating LCTV will modulate some phase and the phase-modulating LCTV will modulate some amplitude. This, in fact, does occur, but the effect is small. When the LCTV is in the phase-modulating mode, an amplitude modulation of less than 5% can be observed. The phase modulation from the amplitude-modulating LCTV was harder to observe because an interferometer had to be constructed around the LCTV. No visible fringe shift was observed as the input was varied from minimum to maximum brightness, although it is likely that some phase modulation was present. A small amount of amplitude and phase mixing can be corrected with minor variations in inputs. The overall phase distortions inherent in the phase-modulating LCTV can also be corrected by using a point-diffraction interferometer.⁵ The amount of distortion seems to vary among devices from less than one fringe across the device to more than two.

In conclusion, a technique that should allow full complex representation of filters for a variety of applications has been presented. The technique is based on previous experimental results, which have verified independently the amplitude- and phase-modulating properties of LCTV's. The architectures presented here represent two approaches to combining these effects.

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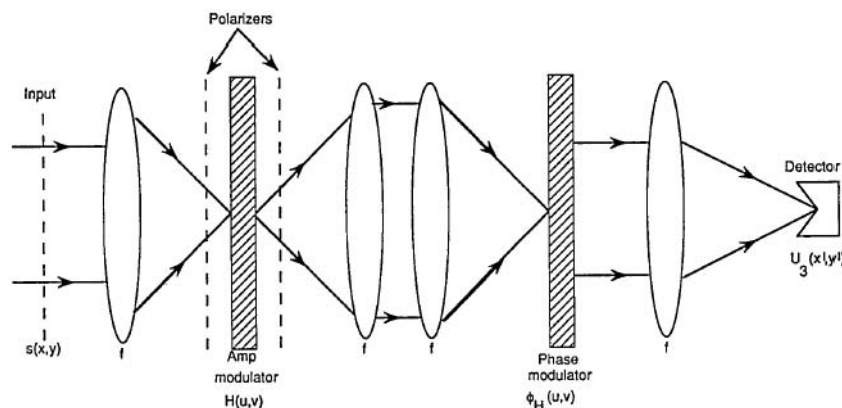


Fig. 3. Realistic architecture for combining amplitude and phase in a filtering operation.

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Metrics for assessing pattern-recognition performance

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Various metrics used to measure correlation filter performance are discussed. Their similarities and deficiencies are noted, and modifications are suggested. A computer simulation is included to highlight these differences.

Within the past decade there has been a considerable increase in the research effort to improve filters for optical correlators and the means of implementing them on spatial light modulating (SLM) devices. With so much activity it would be useful if a common set of performance parameters could be agreed on by researchers in the field. It would also be useful if a common set of images could be used in testing the algorithms and systems. Toward the first goal, Kumar and Hasselbrook¹ have proposed a new measure of performance, the peak-to-correlation energy (PCE), which is a modification of that previously proposed by Dickey and Romero.² The PCE is shown in Eq. (1) below. We would like to discuss its properties in relation to two other measures that have been used and to suggest a modification to improve these measures. The two other measures referred to are the so-called Horner efficiency³ η_H , shown in Eq. (2), and the signal-to-noise ratio (SNR) measure defined in Eq. (3) as the correlation peak value divided by the rms noise outside the full width at half-maximum (FWHM) of the correlation peak.⁴ Let us label this metric SNR_1 . That is,

$$\text{PCE} = C_{(0)}^2 / \sum_i C_{(x_i)}^2, \quad (1)$$

$$\eta_H = C_{(0)}^2 / \sum_i s_{(x_i)}^2, \quad (2)$$

$$\text{SNR}_1 = C_{(0)} / \left[\frac{1}{N} \sum_i C_{(x_i > \text{FWHM})}^2 \right]^{1/2}, \quad (3)$$

where $C_{(0)}$ is the maximum value of the correlation, N is the array size, and $s(x)$ is the input image to the correlator, where we use the usual shorthand to let x represent both orthogonal coordinates in the plane. First, we point out some similarities between these three metrics. For the phase-only or binary-phase-only filter, the correlation peak is usually only one pixel wide so that $\sum_i C_{(x_i)}^2 = C_{(0)}^2 + \sum_i C_{(x_i > \text{FWHM})}^2$. This means that

$$\text{PCE} = \text{SNR}_1 / (\text{SNR}_1 + N). \quad (4)$$

Another equality is that, for the phase-only and binary-phase-only filters, η_H and PCE are identical. The reasoning is as follows. The PCE is defined entirely in terms of energy in the correlation plane. The denominator of the Horner efficiency is the energy in the input plane. If there is no attenuation in the Fourier plane of a standard-frequency

plane correlator, then by Parseval's theorem, the energies in both planes are the same and

$$\text{PCE} = \eta_H. \quad (5)$$

Of course if there is an amplitude mask in the Fourier plane, then some of the energy is lost and η_H is smaller than the PCE.

Another measurement frequently used in correlation filter algorithm development is

$$\text{SNR}_i = E^2[C_{(0)}] / \text{VAR}[C_{(0)}], \quad (6)$$

i.e., the ratio of the average to the variance of a single point, the correlation peak. This requires the iteration or preparation of a sufficiently large number of statistically independent noise samples (typically 100 to 500) to gather the output statistics. For this reason, it would be impractical to use this measure experimentally to assess the SNR of a real correlator. From this point of view, the PCE or SNR_1 would be a better choice. However, the PCE is analytically tractable and easier to use in mathematical analysis.¹ It is, however, a number, unlike the SNR_1 , that varies from 0 to 1.0, so that direct numerical comparisons cannot be made.⁵

The statement is often made that the matched filter gives the largest SNR of any possible correlation filter. This is only true when the SNR is defined as in Eq. (6). We shall see in a simulation below that several other definitions, for example SNR_1 of Eq. (3), give higher numerical values. Of course, higher is not necessarily better, as will also be discussed below. We are seeking here a metric that incorporates the best features of all the above, and is still convenient to use in practice.

Effects of dc Level

We have discovered that the dc or bias level in the correlation plane has a considerable effect on the numbers quoted for the PCE or SNR_1 . This should not be the case because the bias level in the correlation plane really does not affect the detectability or false alarm rate. Also, in a real system, the dc level is easily removed by simply using a coupling capacitor between the detector and its electrical output terminal. To show the effect of the dc or bias level we computer simulated a correlation, using a girl's face as the input signal, a 64×64 array in a zero-filled 128×128 array. We simulated the standard-frequency plane (4-f) correlator with either a classical matched filter, or a phase-only filter. White noise (zero-mean, Gaussian-distributed) was added to the input signal. The input SNR ratio was defined as

$$\text{SNR}_{\text{in}} = E[s_{(x)}] / \sigma_{[n(x)]}, \quad (7)$$

where σ represents the standard deviation or the noise array $n(x)$. In order to make the metric for SNR insensitive to the average dc level, we extracted the best features of the PCE and SNR_1 and defined PCE' ⁶

$$\text{PCE}' = C_{(0)}' / \left[\frac{1}{N} \sum_i C_{(x_i \neq 0)}'^2 \right]^{1/2}, \quad (8)$$