Diffractive ferroelectric liquid-crystal shutters for unpolarized light

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Electro-optic modulators using ferroelectric liquid-crystal technology have generally been limited to use with polarized light. It is possible, however, to construct a diffractive array of ferroelectric liquid-crystal phase modulators that can act as a shutter for unpolarized light. We have built two types of polarization-independent diffractive shutter based on this principle. We describe their principles of operation and performance.

Electro-optic modulators using ferroelectric liquid crystals (FLC's) act as rotatable wave plates. Since surface-stabilized FLC's (SSFLC's) have two stable states, they act as wave plates that have two possible (voltage-selectable) orientations.[1] These devices may be used as binary phase or polarization modulators for polarized light. Shutters for polarized light are typically constructed by using the SSFLC as a polarization modulator between crossed polarizers. Another type of shutter for polarized light has been built based on the principle of switchable total internal reflection.[2] Neither of these devices can completely modulate unpolarized light. Here we describe the operating principle, construction, and performance of a class of FLC-based shutter whose operation is independent of polarization.

A linear array of phase modulators forms a diffraction grating. If the linear array of modulators forming the grating are of equal width and are set to produce relative phase shifts of (0, π, 0, π, . . . , 0, π), then the intensity of light transmitted into the zeroth diffraction order will be zero. All outgoing light is scattered into higher diffraction orders. As the pixels of the array switch between phase shift states of (0, π, . . . , 0, π) and (0, 0, . . . , 0, 0) the incident beam will be alternately transmitted or fully diffracted.

Figure 1 depicts a simple imaging system composed of a single lens and a diffractive shutter. Light with electric-field vector $\vec{U}_o(x_o, y_o)$ from an object passes through the shutter (SSFLC array) and lens to form an image $\vec{U}_i(x_i, y_i)$. It is well known that the field projected onto the image plane is a convolution of the input image with the transmittance function of the lens aperture.[3] In this case the transmittance function is that of a set of strips (pixels) all of whose phase delays are 0 or whose phase delays alternate between 0 and π. The image electric field $\vec{U}_i(x_i, y_i)$ as a function of the object electric field $\vec{U}_o(x_o, y_o)$ is

$$\vec{U}_i(x_i, y_i) = \frac{1}{M}\left[\frac{1}{2}(\mathbf{T}_2 + \mathbf{T}_1)\vec{U}_o\left(x_o = -\frac{x_i}{M}, y_o = -\frac{y_i}{M}\right) + \frac{1}{\pi}\sum_{m\ \mathrm{odd}} \frac{(-1)^{(m-1)/2}}{m}(\mathbf{T}_2 - \mathbf{T}_1) \times \vec{U}_o\left(x_o = \frac{m d_i \lambda/\lambda_g - x_i}{M}, y_o = -\frac{y_i}{M}\right)\right]. \quad (1)$$

Here $\mathbf{T}_1$ and $\mathbf{T}_2$ are the Jones matrices[4] of the modulators in states 1 and 2. If $\mathbf{T}_2 = -\mathbf{T}_1$ (π modulation of relative phase), then the zeroth-order term [the first term of Eq. (1)] vanishes. If $\mathbf{T}_2 = \mathbf{T}_1$ (no modulation), then all the higher-order terms vanish, leaving only the undeflected image. The quantity λ_g is the period of the diffraction grating (twice the width of a pixel), and (x_i, y_i) and (x_o, y_o) are image and object plane coordinates.

Using Eq. (1) under the assumption that the diffraction orders are nonoverlapping, we find the intensity of light in the image plane in these two cases to be

$$I_i(x_i, y_i) = \begin{cases} \left(\dfrac{1}{M}\right)^2 I_o\left(x_o = -\dfrac{x_i}{M}, y_o = -\dfrac{y_i}{M}\right) & \text{open} \\ \left(\dfrac{1}{M}\right)^2\left(\dfrac{2}{\pi}\right)^2 \displaystyle\sum_{m\ \mathrm{odd}} \left(\dfrac{1}{m}\right)^2 I_o\left(x_o = \dfrac{m d_i \lambda/\lambda_g - x_i}{M}, y_o = -\dfrac{y_i}{M}\right) & \text{closed} \end{cases}. \quad (2)$$

Here $M = d_i/d_o$, where d_i is the image distance from the lens and d_o is the object distance. When the shutter is open the lens forms an ordinary image. When the shutter is closed the ordinary image vanishes and a number of copies of the image (diffraction orders) appear at increasing distances from the center of the image plane. The first-order image is offset from the center by an angle θ_1 determined by $\sin(\theta_1) = \lambda/\lambda_g$. We define θ_1 to be the angular field of view. So long as the angular size of the image (equal to the angular size of the object) is less than θ_1, the first-order images will not overlap the position of the central

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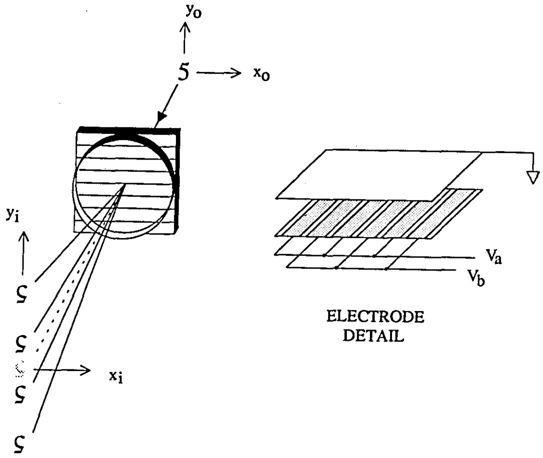

Fig. 1. Formation of diffracted images by a lens combined with a SSFLC array. Also shown is a schematic of the electrode structure of the array. When $V_a = V_b$ all modulator strips are in the same state and no diffraction occurs. When $V_a = -V_b$ light passing through adjacent strips differs in phase by π, thus producing diffraction.

image, and the diffraction grating effectively acts as a shutter.

Although in this example we have implicitly considered only coherent light, the principle underlying operation of the shutter applies equally well to light that is temporally and spatially incoherent.

To build the polarization-independent diffractive shutter we need electro-optic modulators that can produce voltage-selectable, polarization-independent phase shifts of 0 and π. We describe two methods that achieve this using FLC modulators.

SSFLC modulators act as rotatable wave plates with two possible optic axis orientations (selected by the polarity of an applied voltage). The thickness D and birefringence $\Delta n = n_e - n_o$ of the FLC layer determine the retardance $\Gamma = 2\pi D\Delta n/\lambda$ of the wave plate (half-wave, quarter-wave). The angle between the two possible wave-plate orientations ϕ_1 and ϕ_2 is equal to twice the tilt angle[1] ψ of the FLC molecules. The Jones matrix of the FLC wave plate is

$$\mathbf{T}_n = \exp(-i\chi)\begin{bmatrix} e^{-i\Gamma/2}\cos^2(\phi_n) + e^{i\Gamma/2}\sin^2(\phi_n) & -2i\sin(\Gamma/2)\sin(\phi_n)\cos(\phi_n) \\ -2i\sin(\Gamma/2)\sin(\phi_n)\cos(\phi_n) & e^{i\Gamma/2}\cos^2(\phi_n) + e^{-i\Gamma/2}\sin^2(\phi_n) \end{bmatrix}, \tag{3}$$

where $\chi = \pi(n_e + n_o)D/\lambda$.

Among the most useful FLC's are those with tilt angles near 22.5° (low tilt) or 45° (high tilt) that have wave-plate rotation angles of 45° and 90°, respectively. A half-wave plate rotatable through 45° can be used to change vertically polarized light to horizontally polarized light. A half-wave plate rotatable through 90° can be used to shift the phase of light by π.

By forming a tandem modulator in which light passes through two low-tilt half-wave plates that switch in opposite direction [Fig. 2(a)], a voltage-selectable polarization-independent 0, π phase modulator is obtained. The Jones matrices for the two relevant states of the tandem FLC modulator are

$$\mathbf{T}_1 = e^{-2i\chi}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{T}_2 = -e^{-2i\chi}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{4}$$

The relationship $\mathbf{T}_1 = -\mathbf{T}_2$ indicates a relative phase shift of π. This modulator has the additional property that it is polarization preserving. Outgoing light will have the same polarization as incoming light; only the phase is altered.

With more recently developed high-tilt materials (e.g., tilt angle of 44° for Chisso[5] CS-2004), a single SSFLC modulator can produce a selectable, polarization-independent phase shift of 0 or π. The Jones matrices for the states ($\phi_1 = 0$, $\phi_2 = \pi$, $\Gamma = \pi$) of this modulator are

$$\mathbf{T}_1 = e^{-i\chi}\begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix}, \qquad \mathbf{T}_2 = -e^{-i\chi}\begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix}. \tag{5}$$

Again the relationship $\mathbf{T}_1 = -\mathbf{T}_2$ indicates a relative phase shift of π. Though this modulator is not polarization preserving, it can be made so by placing it in series with a fixed-orientation half-wave plate. In this case the new Jones matrix is $\mathbf{T}_k' = \mathbf{T}_{\lambda/2}\mathbf{T}_k$ [Fig. 2(b)],

$$\mathbf{T}_{\lambda/2} = -\begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix}, \qquad \mathbf{T}_1' = e^{-i\chi}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\mathbf{T}_2' = -e^{-i\chi}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{6}$$

Phase modulators made from high-tilt FLC's are easier to fabricate since registration of two arrays of pixels (as in the tandem modulator) is not necessary.

We have built diffractive shutters of both the tandem-array, low-tilt FLC and single-arrray, high-tilt FLC types. The low-tilt FLC used was Merck[6] ZLI-3654 (tilt angle 25°), and the high-tilt FLC was Chisso[5] CS-2004 (tilt angle 44°). The 120-μm-wide pixels were on a 125-μm pitch, leaving a 5-μm interpixel gap. At the He–Ne laser wavelength of 633 nm the field of view of the shutter is $\lambda/\lambda_g = 0.633/250 = 0.0025$ rad (0.14°). The illuminated portion of the arrays was approximately 150 pixels in length, with a pixel height of 1 mm. The two FLC layers of the tandem array were separated by approximately 1.1 mm (twice the thickness of the glass used).

The optical system used for testing the on/off (shutter open/closed) intensity ratio is illustrated in Fig. 3(a). The He–Ne laser was unpolarized. The on/off intensity ratio measured for the tandem array was approximately 70:1, while the single-layer, high-tilt FLC array produced a contrast of approximately 30:1. The fact that light was not fully extinguished when the shutter was closed probably indicates that the FLC layer was not exactly the right thickness or that light passing through the gaps betwen pixels was a limiting factor.

In Fig. 3(b) we show a diagram of the optics used for the imaging experiment in which the single-array, high-tilt SSFLC diffractive shutter was used. An unpolarized incandescent white-light source was used to illuminate a transparency of the numeral 5. A diffuser was placed in front of the light source to even out the illumination. This light passes through the high-tilt FLC diffractive array and a lens to form an image that was viewed through a microscope focused on the image plane. Owing to wavelength-dependent retardance of the FLC wave plates, the array does not diffract well in the blue (the FLC thickness was chosen to obtain half-wave plate operation in the red). For this reason white light from the illuminator was passed through a 650-nm long-pass color filter. On/off photographs of the image 5 seen through the microscope are shown in Fig. 4. In the off state (shutter closed) the center image is seen to be greatly attenuated. The first- and third-order diffracted images that are seen in the off photograph are each brighter than the center image.

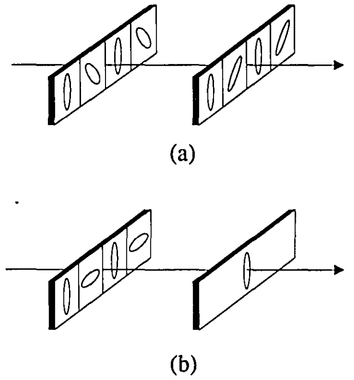

Fig. 2. Orientations of SSFLC modulators that produce an alternating pattern of phase shifts $(0, \pi, \ldots)$. The ellipses in the figure represent the FLC optic axis orientations. (a) The relationship of SSFLC wave plates in the tandem, low-tilt SSFLC array. One wave plate of a pair rotates by +45°, while the other rotates by −45°, which results in a 90° difference in orientation. (b) The orientations of the SSFLC wave-plate optic axes for the single-layer, high-tilt SSFLC array. Also shown in (b) is an optional wave plate that makes the modulator polarization preserving.

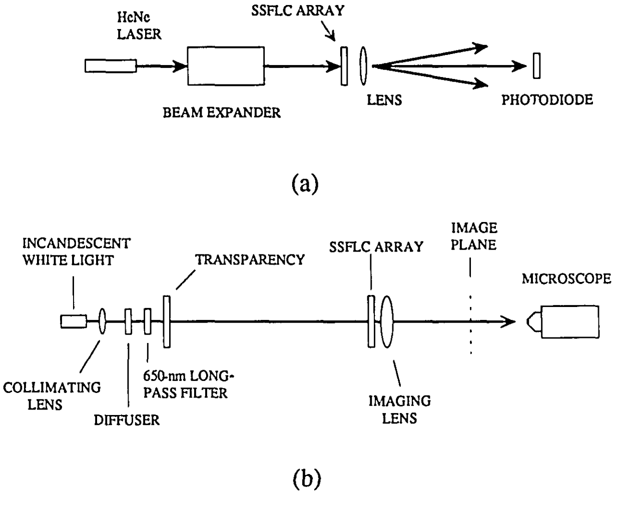

Fig. 3. (a) Experimental configuration used to measure on/off contrast ratios. (b) The arrangement used for the imaging experiment.

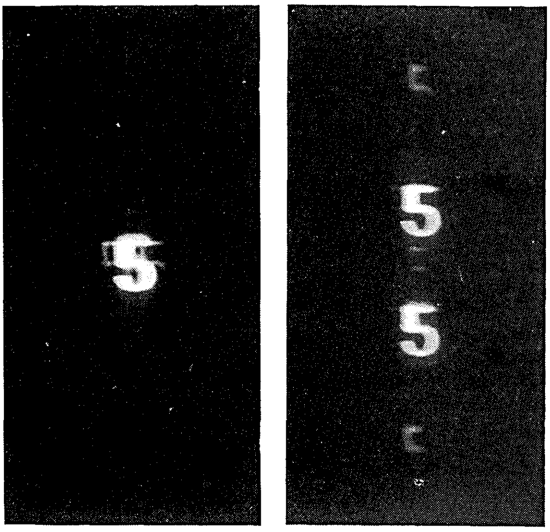

Fig. 4. Left: photograph of the image produced with the shutter open. Right: photograph of the image with the shutter closed.

We have demonstrated the operation of diffractive SSFLC electro-optic shutters. Compared with other types of electro-optic shutter, these have the advantage of polarization independence and of being polarization preserving. Since no polarizers are required, these shutters are extremely efficient. Although the field of view of our prototype was small, finer lithography or longer wavelengths would widen it considerably. In principle, the pixels can be made as narrow as the FLC film is thick before fringing fields from the electrodes prevent switching throughout the entire FLC film thickness. At this limit the grating has a periodicity $\lambda_g = 2d$, which, for a half-wave thickness, produces a field of view given by $\sin\theta = \Delta n$. Typical FLC's have $\Delta n \sim 0.15$, but there is no reason why (as has been done for nematics) the birefringence could not be doubled to 0.3 by formulation of special-purpose materials. The remaining limitation is wavelength dependence of the shutter. A complete off state is obtained only at the wavelength for which the FLC retardance is exactly a half-wave. However, with an incident spectral width of ±20% (e.g., 450–675 nm), a 25:1 contrast could still be obtained.

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