Analog optical phase modulator based on chiral smectic and polymer cholesteric liquid crystals

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A high-speed analog optical phase modulator based on chiral smectic and cholesteric liquid crystals is discussed. The chiral smectic liquid-crystal device functions as a variable-orientation half-wave retarder, whereas the polymer cholesteric liquid-crystal film acts as a polarization-preserving mirror. We use circular Jones calculus to describe optical phase modulation, using a half-wave retarder of variable orientation acting on circularly polarized light. The phase induced by this modulator is achromatic. Analog phase modulation of nearly 360° is demonstrated with a device switching time of 200 μs at 25 °C. © 1995 Optical Society of America

Analog phase modulators are used to implement tunable optical filters, dynamic phase masks, adaptive optics, reconfigurable optical interconnects, and agile beam-steering devices. Liquid-crystal phase shifters are frequently used in these applications because they possess the desirable properties of large modulation depth per unit length, low voltage and power dissipation, potential for high modulator density, low cost, and large aperture. These phase shifters are implemented by either retardation modulation or polarization modulation. Because the phase shift of a variable retarder is due to an optical path-length change, it is inherently chromatic. If the phase change is due to polarization modulation, as it is for the modulator discussed here, the induced phase is achromatic. This wavelength independence can have advantages if the modulator is to be used to implement a liquid-crystal optical phased array.[1]

An analog phase shifter based on polarization modulation is implemented by rotation of the optic axis of a half-wave retarder in a plane transverse to the propagation of a circularly polarized field. On transmission through the retarder, the circularly polarized incident light undergoes a handedness change and receives a phase change equal to twice the rotation of the half-wave retarder. Such a rotative retarder can be implemented with planar aligned chiral smectic liquid crystals (CSLC's). The tilt angle of CSLC materials limits the effective optic axis rotation to 90° or less; thus the phase modulation for a single pass through a CSLC half-wave retarder is at most 180°. This modulation depth may be increased by cascading devices[2] or by resonant enhancement.[3]

The device presented here uses two passes through a single retarder to increase modulation depth. If a conventional mirror is placed behind a CSLC half-wave retarder, the phase induced on a circularly polarized field in the first pass through the retarder is canceled by a phase of opposite sign induced in the reverse pass. However, if a quarter-wave retarder is placed in front of the mirror, the modulation depth is doubled by the second pass. This increase in modulation depth is realized because the quarter-wave plate/mirror combination preserves the handedness of circular polarization. Here we use a thin film of cholesteric liquid crystals exhibiting the planar texture to act as a handedness-preserving mirror.

Cholesteric liquid crystals[4] (CLC's) can be modeled as layers of nematic liquid crystals in which the director orientation of each layer is rotationally displaced to trace out a helix. The helical structure forms a Bragg grating that reflects circularly polarized light of the same handedness as the helix. The wavelength of maximum reflection is $\lambda_0 = nq$, where q is the pitch and n is the average refractive index of the nematic layers. The selective reflection occurs over a bandwidth $\Delta\lambda = \Delta nq$, where Δn is the birefringence of the nematic layers. Light with circular polarization of the opposite handedness is fully transmitted, as is light having a wavelength outside the selective reflection band. A film thickness of approximately 10 pitch lengths is required for >90% reflectivity.

The operation of the phase modulator shown in Fig. 1 can be described by Jones calculus with circular basis vectors.[5] First consider the ideal situation in which the circular polarizer, the CSLC half-wave retarder, and the CLC mirror are achromatic. An ideal right-circular polarizer may be described by the Jones matrix:

$$P_R = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}. \qquad (1)$$

A half-wave retarder with optic axis orientation α has the Jones matrix

$$H(\alpha) = \begin{bmatrix} 0 & j\exp(j2\alpha) \\ j\exp(-j2\alpha) & 0 \end{bmatrix}. \qquad (2)$$

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The matrix for reflection from an ideal left-helical CLC mirror is

$$C_L = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}. \qquad (3)$$

For incident right-circularly polarized light, multiplication of the input vector, $R_p = [0\ 1]^T$, and the above matrices gives the reflected electric-field vector:

$$\hat{E}_r = P_R H(-\alpha) C_L H(\alpha) P_R R_p = \exp(j4\alpha) \begin{bmatrix} 0 \\ -1 \end{bmatrix}. \qquad (4)$$

Equation (4) shows that the phase shift is four times the optic axis rotation of the CSLC half-wave retarder. Thus a CSLC material having an effective optic axis rotation of 90° can achieve a phase-modulation depth of 360°.

Now consider the case in which just the CSLC retarder is chromatic. The retardation can be represented by $\Gamma = \pi + \xi$, where ξ is the wavelength-dependent departure in retardation from a half-wave. The matrix for the retarder becomes

$$G(\xi, \alpha) = \begin{bmatrix} -\sin(\xi/2) & j\exp(j2\alpha)\cos(\xi/2) \\ j\exp(-j2\alpha)\cos(\xi/2) & -\sin(\xi/2) \end{bmatrix}. \qquad (5)$$

Replacing the H matrices in Eq. (4) by G matrices as defined in Eq. (5), one obtains the reflected field component for the case of a chromatic CSLC retarder:

$$\hat{E}_r = \exp(j4\alpha) \begin{bmatrix} 0 \\ -\cos^2(\xi/2) \end{bmatrix}. \qquad (6)$$

The deviation in retardance with wavelength is manifested as a loss in amplitude. However, the phase modulation is achromatic, depending only on the orientation of the optic axis, α.

The phase modulator discussed in this Letter is based on a planar-aligned CSLC half-wave retarder and a polymer cholesteric liquid-crystal (PCLC) mirror. We fabricated the PCLC mirror by using a side-chain liquid-crystal polymer exhibiting the cholesteric phase. This film is approximately 4.5 μm thick and reflects 92% of left-circularly polarized 632.8-nm laser light. The PCLC mirror offers a distinct advantage over a quarter-wave retarder and a conventional mirror in that the reflecting surface has the potential to be situated in close contact with the active chiral smectic retarder. In such an integrated device, the beam undergoes minimal diffraction between passes through the half-wave retarder. This is important for efficient high-resolution multiple-pixel phase modulators.

The CSLC cell was fabricated with 2-μm spacers and a buffed polymer alignment. The device was measured to be a half-wave retarder at 646 nm for no voltage applied. The retarder demonstrated an analog rotation of its optic axis from its zero-field monostable state to approximately 88° for applied ac voltages having amplitudes as high as 5 V. As the frequency of the applied voltage was increased from 0.2 Hz to 2 kHz, the optic axis rotation became more linear in relation to the applied electric field. During switching, a small (10%) change in retardation of the device was observed. This change in retardation results from a combination of uniform conical switching and layer tilt with respect to the substrates.[6] However, as discussed above, a retardation change has no effect on phase modulation.

For a voltage of 1-kHz frequency, the 10–90% rise time was measured to be 200 μs, and the 90–10% fall time was 238 μs. The response time can be decreased with an increase in temperature. Fortunately for this type of CSLC material the tilt angle is relatively independent of temperature in the smectic phase.[7] Consequently, an increase in speed obtained by heating the material will not significantly reduce the phase-modulation depth.

A bulk phase modulator using a CSLC retarder and a PCLC mirror was placed in one arm of a Michelson interferometer, as shown in Fig. 2. The other arm contained a PCLC mirror to provide equal amplitudes in each arm. The remainder of the setup consisted

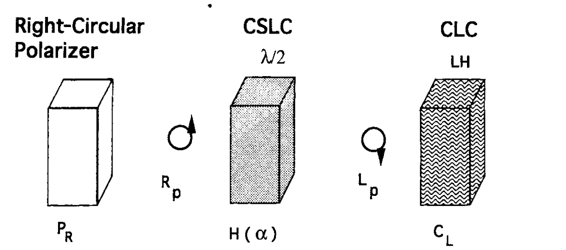

Fig. 1. Schematic of the analog optical phase modulator. A ideal right-circular input polarizer is assumed. The CSLC retarder has a variable orientation, α, and the CLC mirror is left helical. The notation under each device corresponds to that used in Eqs. (1)–(4).

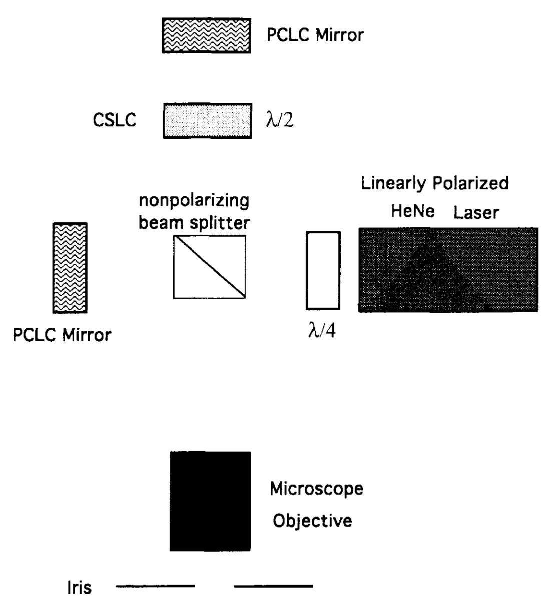

Fig. 2. Schematic of the Michelson interferometer used to demonstrate the bulk phase modulator, which is in one arm. The other arm has just a PCLC mirror. The source is a linearly polarized He–Ne laser. A quarter-wave retarder converts the light to circular polarization. The nonpolarizing beam cube splits the light into the two arms. On reflection, the light is recombined by the cube and interferes at the microscope objective.

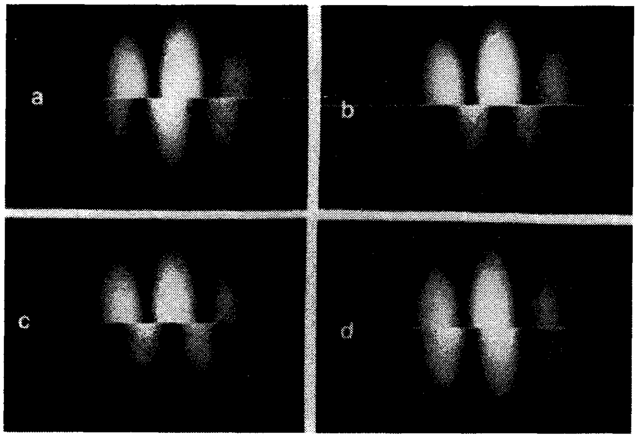

Fig. 3. Photographs of the interference fringes formed by the Michelson interferometer taken at the extreme of the fringe shift for a 0.25-Hz variable-amplitude square-wave voltage. The top parts of the photographs are the reference interference patterns (no applied field). The lower parts show the relative phase modulation for a given amplitude of the square-wave voltage: a, 90° at 1.79 V; b, 120° at 2.0 V; c, 180° at 2.25 V; d, 340° at 3.09 V.

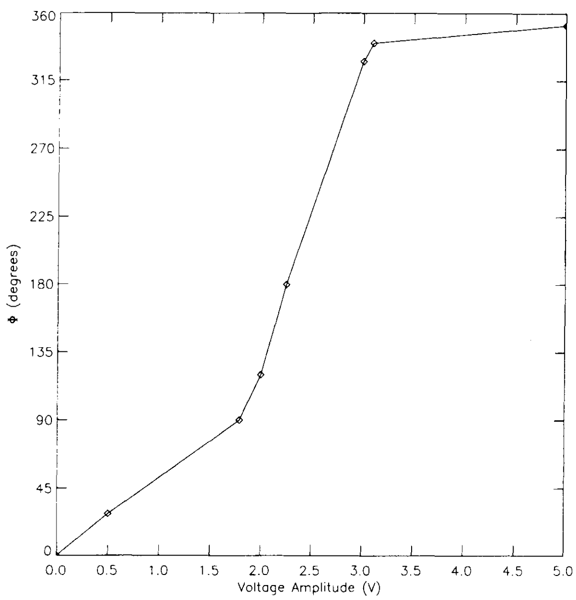

Fig. 4. Phase modulation Φ as a function of voltage amplitude for the modulator discussed here.

of a linearly polarized He–Ne laser, a quarter-wave retarder oriented at 45°, a nonpolarizing beam splitter, a microscope objective, and an iris.

The photographs of Fig. 3 show the fringe patterns of the Michelson interferometer. The top half of each fringe pattern is the reference interference pattern (no applied field). The bottom half of each of pattern shown in Fig. 3 is the extreme fringe shift that is due to application of a 0.25-Hz variable-amplitude square wave voltage to the CSLC retarder. The bottom of Fig. 3a is the extreme fringe shift representing approximately 90° of phase obtained for a square-wave amplitude of 1.79 V. The lower half of Fig. 3b shows the interference pattern obtained with the application of a 2.0-V amplitude square wave, and the bottom part of Fig. 3c shows the fringe shift obtained with a voltage amplitude of 2.25 V. The phase shifts shown in Figs. 3b and 3c are 120° and 180°, respectively. Figure 3d shows a relative phase shift of 340° between the fringes in the top half of the photograph (no voltage applied) and the fringes in the bottom half of the photograph (3.9 V applied). During switching the fringes shifted in an analog fashion to the left with increasing voltage amplitude up to the extreme, then slid back to the right with the voltage polarity change. Based on measurements of the optic axis rotation for the half-wave retarder, the phase-modulation depth for this structure is theoretically 352°. A plot of phase modulation as a function of applied voltage is given in Fig. 4.

An analog phase modulator based on a CSLC half-wave retarder and a PCLC mirror has been demonstrated. It has a modulation depth of nearly 360° and a response time of 200 μs at 25 °C. The large achromatic analog phase modulation obtained with this modulator makes a multiple-phase-level smectic liquid-crystal phased-array grating more feasible. The next step is to integrate the smectic retarder and the mirror and then extend the modulator to multiple pixels.

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